Stellar and Solar Winds

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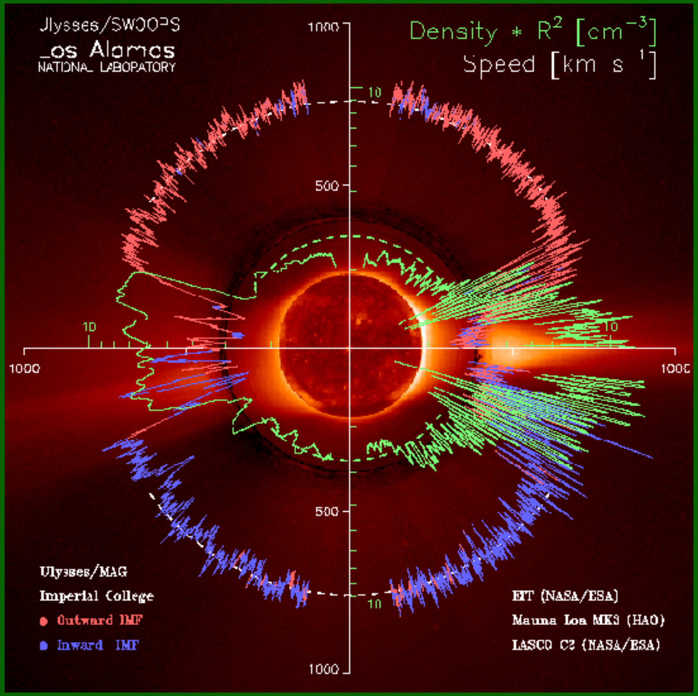
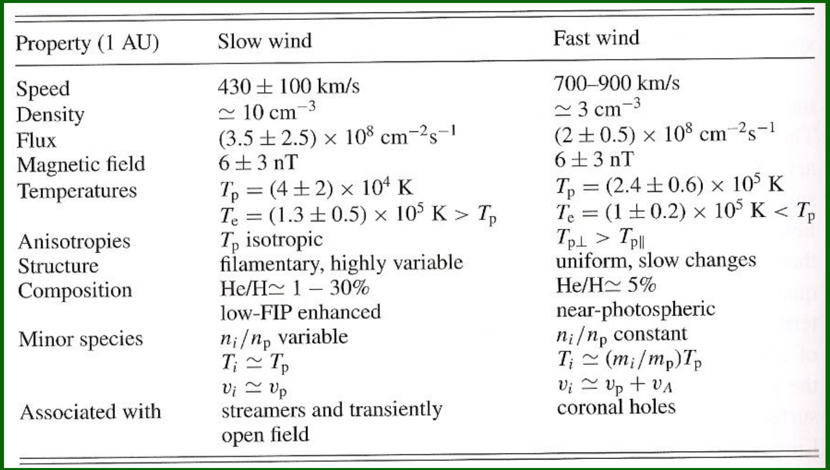
Movie from LASCO/C3 coronagraph on SOHO spacecraft

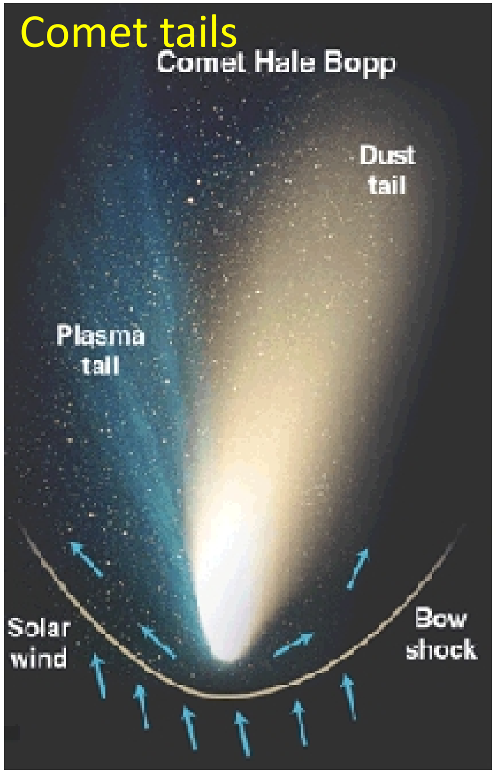


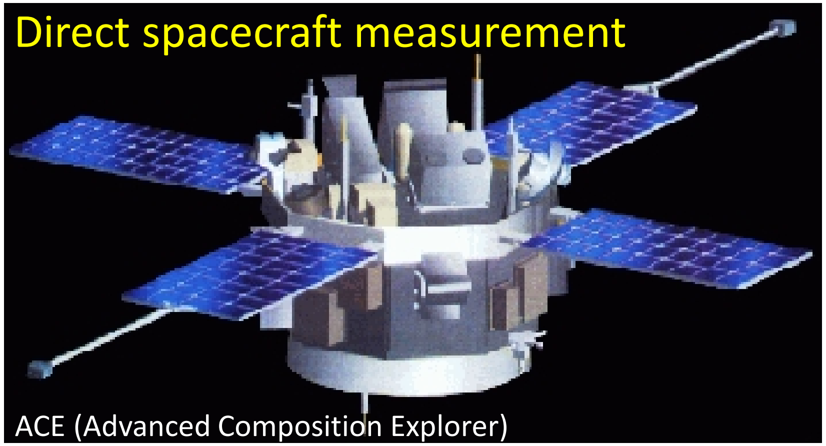


Property (1 AU)	Slow wind	Fast wind
Speed	430 ± 100 km/s	700–900 km/s
Density	$\simeq 10$ cm^{-3}	$\simeq 3$ cm^{-3}
Flux	$(3.5 \pm 2.5) \times 10^8$ cm^{-2}s^{-1}	$(2 \pm 0.5) \times 10^8$ cm^{-2}s^{-1}
Magnetic field	6 ± 3 nT	6 ± 3 nT
Temperatures	$T_p = (4 \pm 2) \times 10^4$ K $T_e = (1.3 \pm 0.5) \times 10^5$ K $> T_p$	$T_p = (2.4 \pm 0.6) \times 10^5$ K $T_e = (1 \pm 0.2) \times 10^5$ K $< T_p$
Anisotropies	T_p isotropic	$T_{p\perp} > T_{p\parallel}$
Structure	filamentary, highly variable	uniform, slow changes
Composition	He/H$\simeq 1 - 30\%$ low-FIP enhanced	He/H$\simeq 5\%$ near-photospheric
Minor species	n_i/n_p variable $T_i \simeq T_p$ $v_i \simeq v_p$	n_i/n_p constant $T_i \simeq (m_i/m_p)T_p$ $v_i \simeq v_p + v_A$
Associated with	streamers and transiently open field	coronal holes

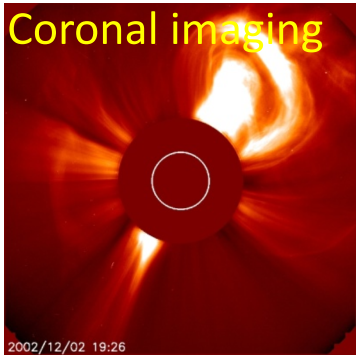
Methods for Detecting and Studying the Solar Wind


Aurora


Comet tails


Direct spacecraft measurement

ACE (Advanced Composition Explorer)

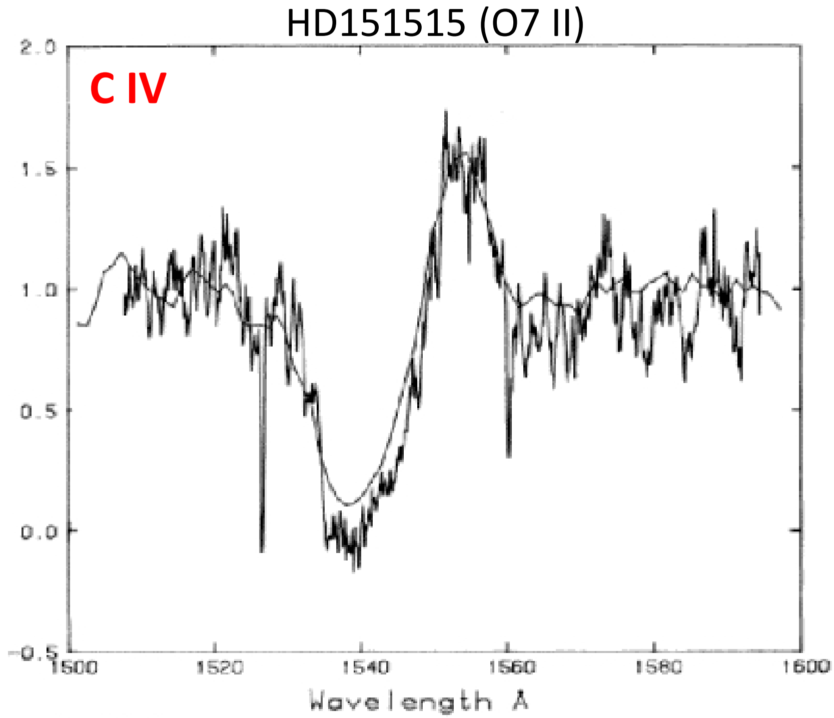

Coronal imaging

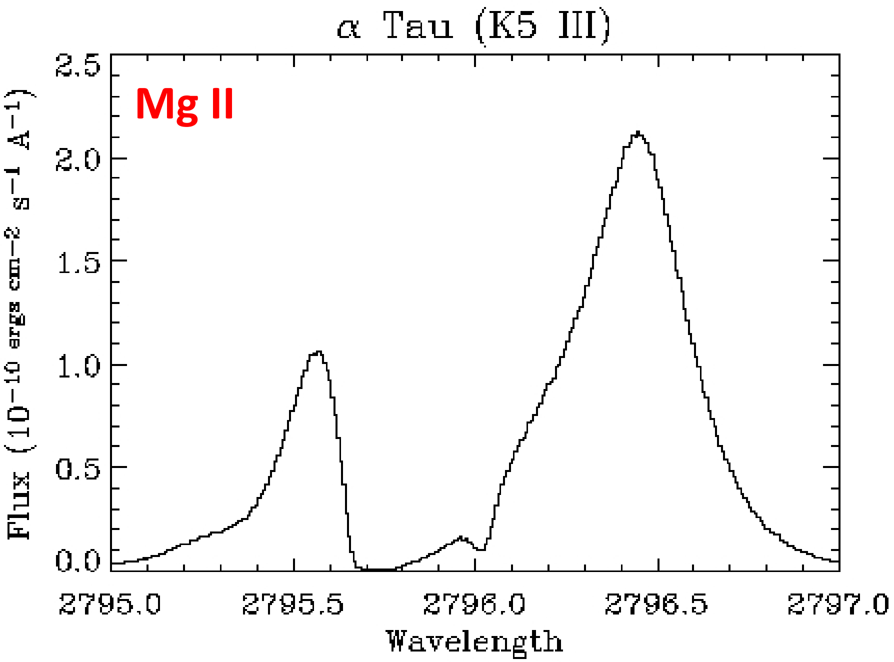
2002/12/02 19:26

Spectroscopic Diagnostics of Stellar Winds

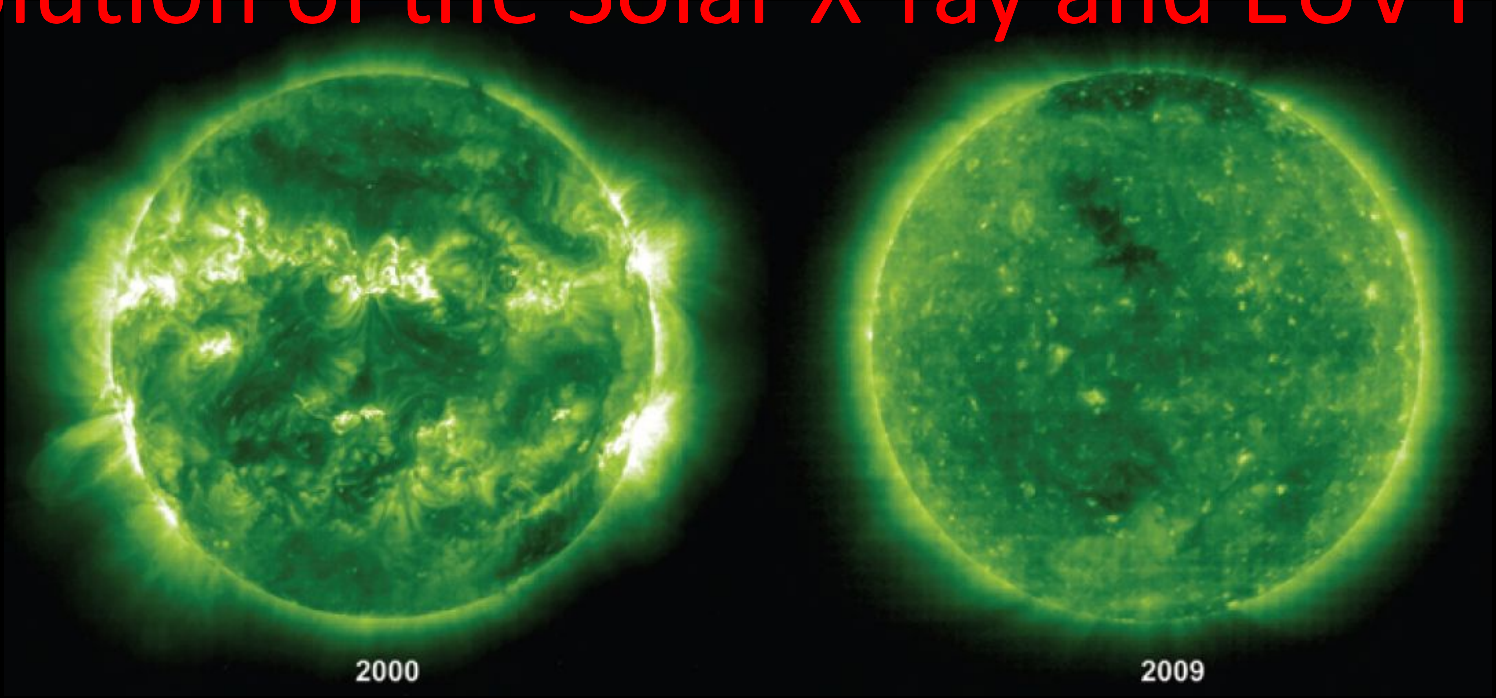
STELLAR WIND COMPARISON

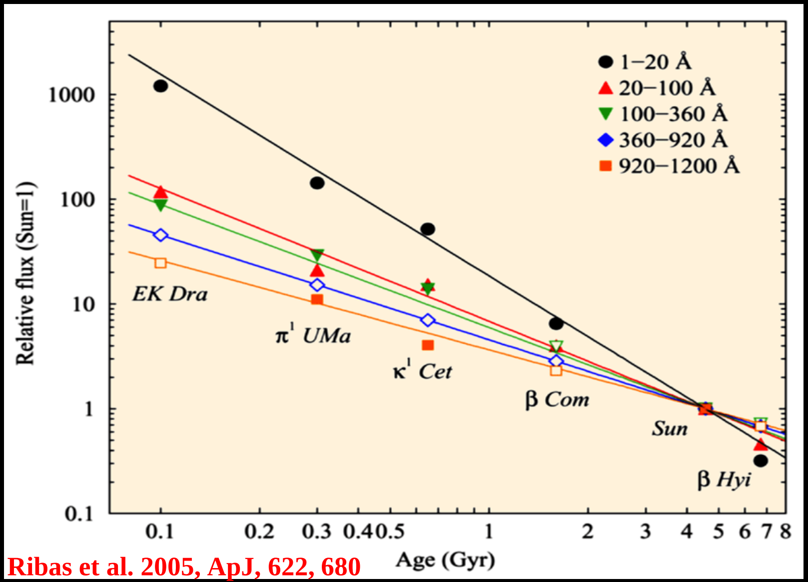
Type of Star	T_{wn} (K)	v (km s^{-1})	$\dot{M}$ ($M_{\odot}$ yr^{-1})	n (1 AU) (cm^{-3})	n (R_{*}) (cm^{-3})
Hot (OB)	10^5	2000	10^{-6}	10^8	10^{11}
Red Supergiant	10^4	10	10^{-7}	10^9	10^9
Red Giant	10^4	30	10^{-11}	10^5	10^8
Sun	10^6	400	10^{-14}	10	10^6





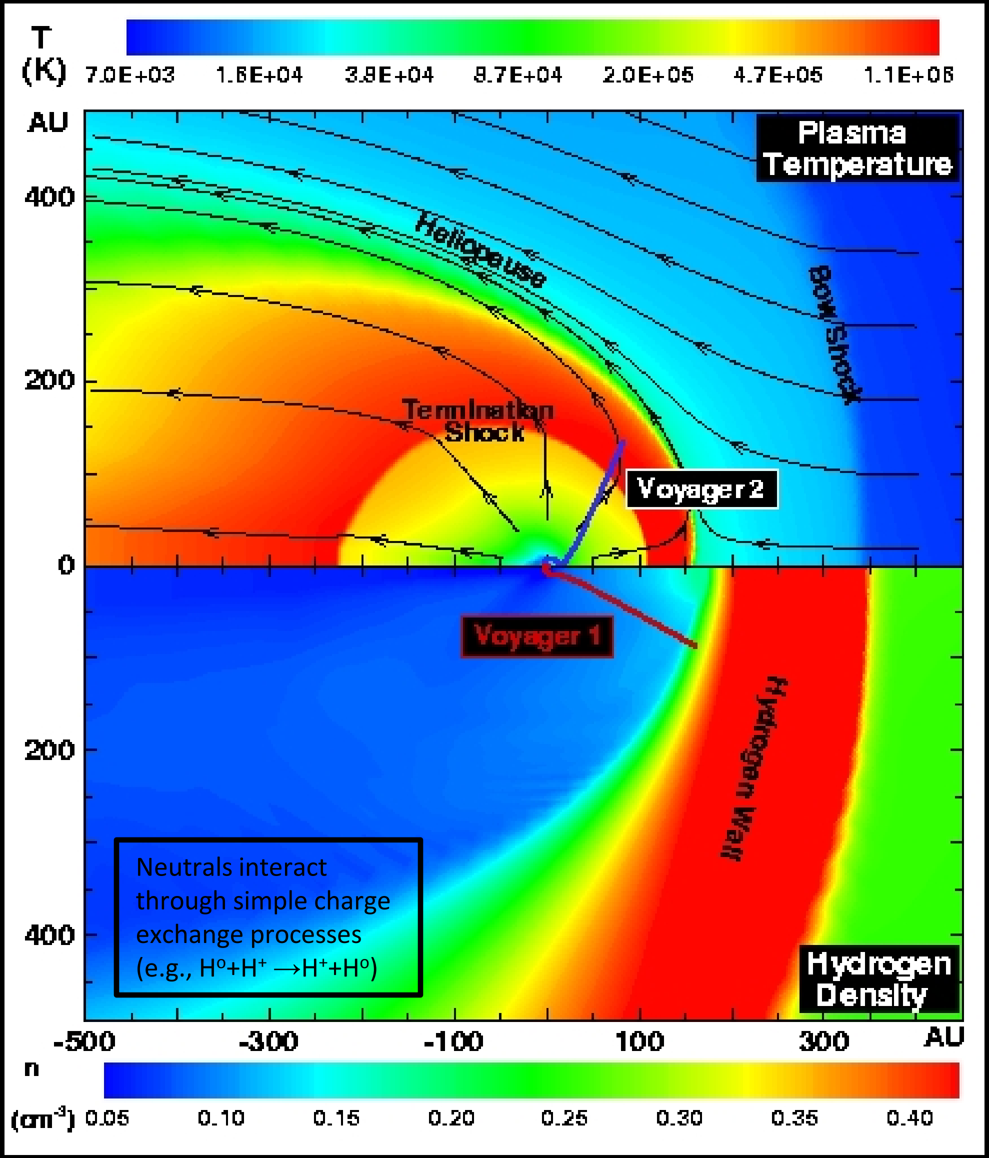
Evolution of the Solar X-ray and EUV FLux





Ribas et al. 2005, ApJ, 622, 680

The Global Heliosphere



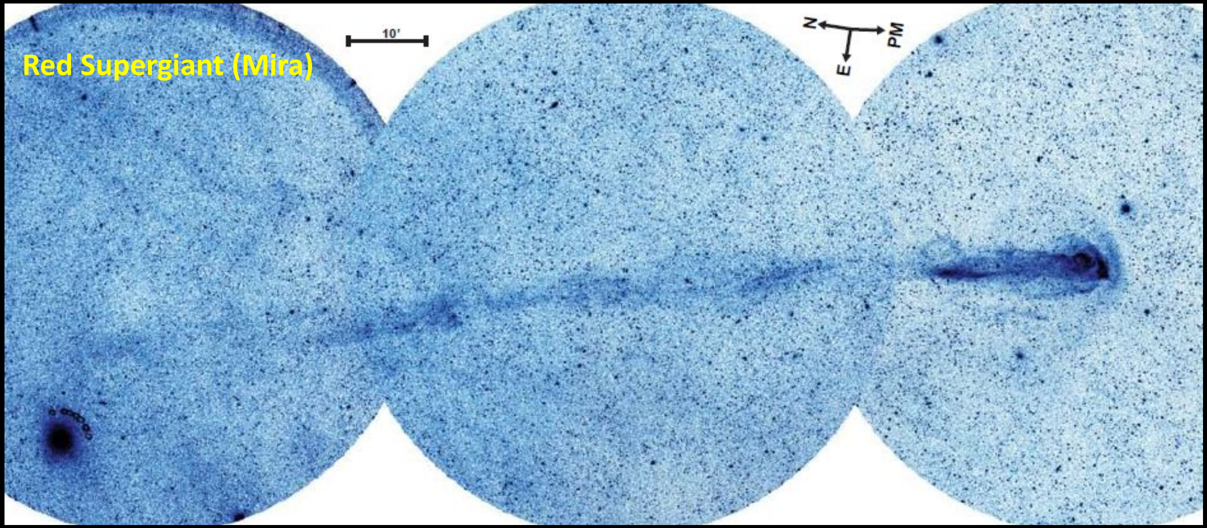
Neutrals interact through simple charge exchange processes (e.g., $H^o+H^+ \rightarrow H^+ + H^o$)

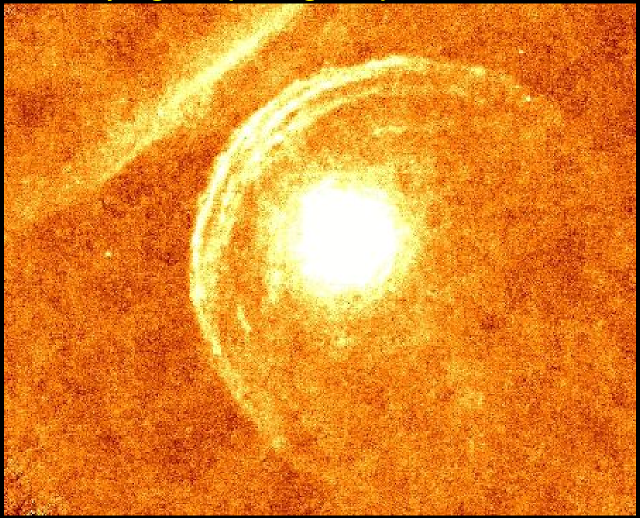
Müller & Zank 2004, JGR, 109, 7104

The only known method of detecting solar-like coronal winds around other stars is by detecting Lyman- absorption from stellar "astrospheres," analogous to our own global heliosphere.

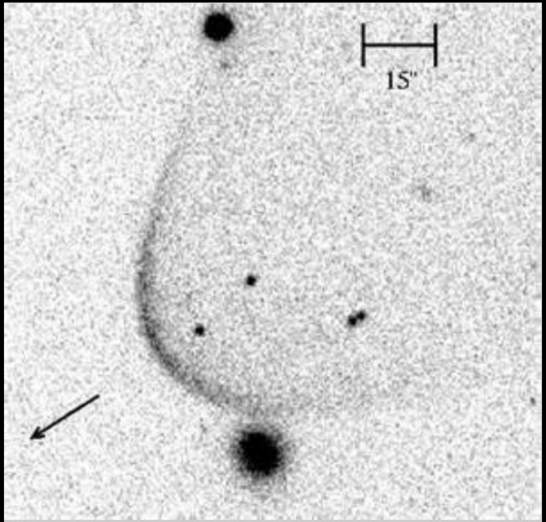
Astrosphere Images


Young Star (LL Ori)

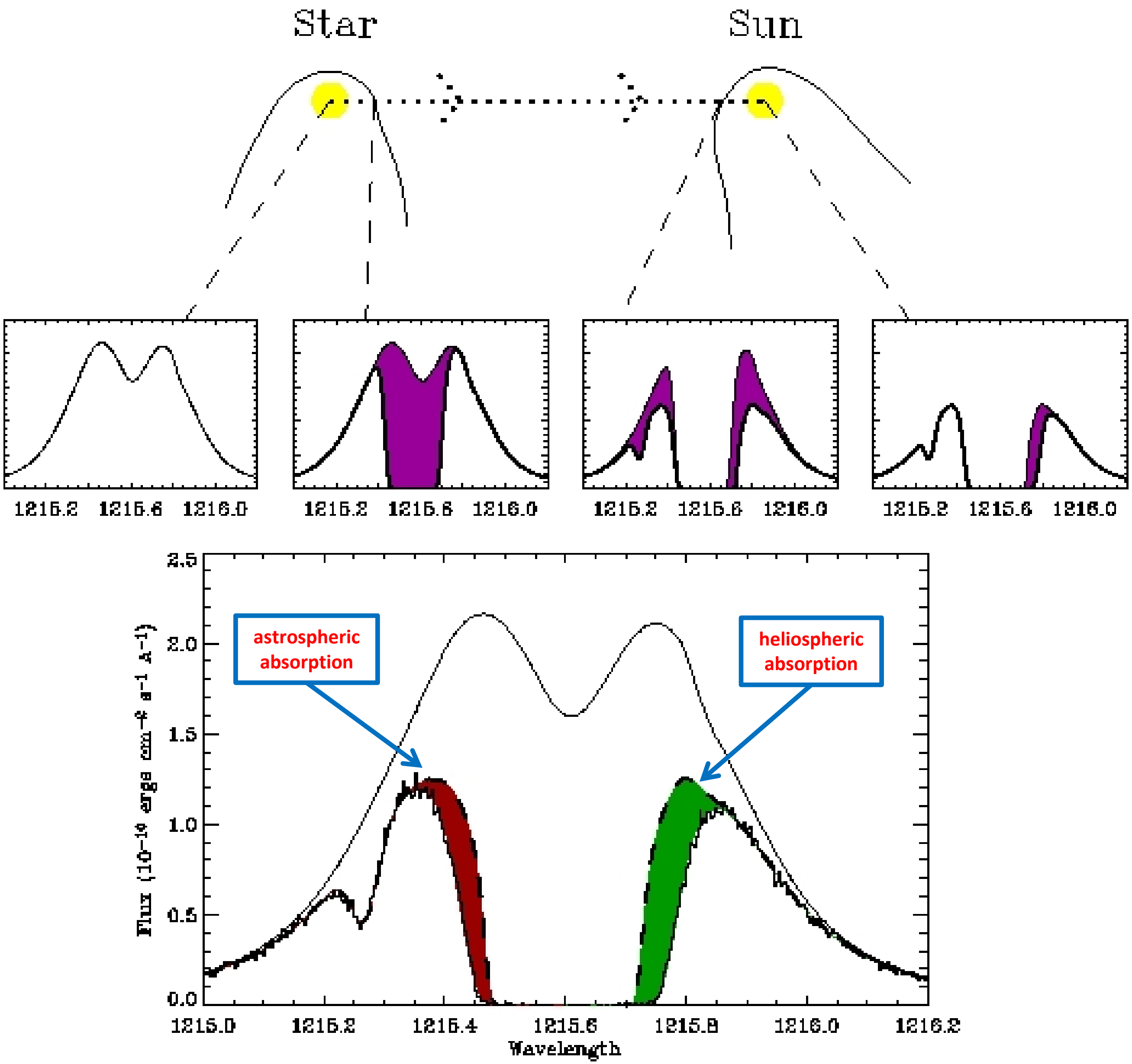

Red Supergiant (Mira)


Red Supergiant (Betelgeuse)


Massive Hot Star


Pulsar

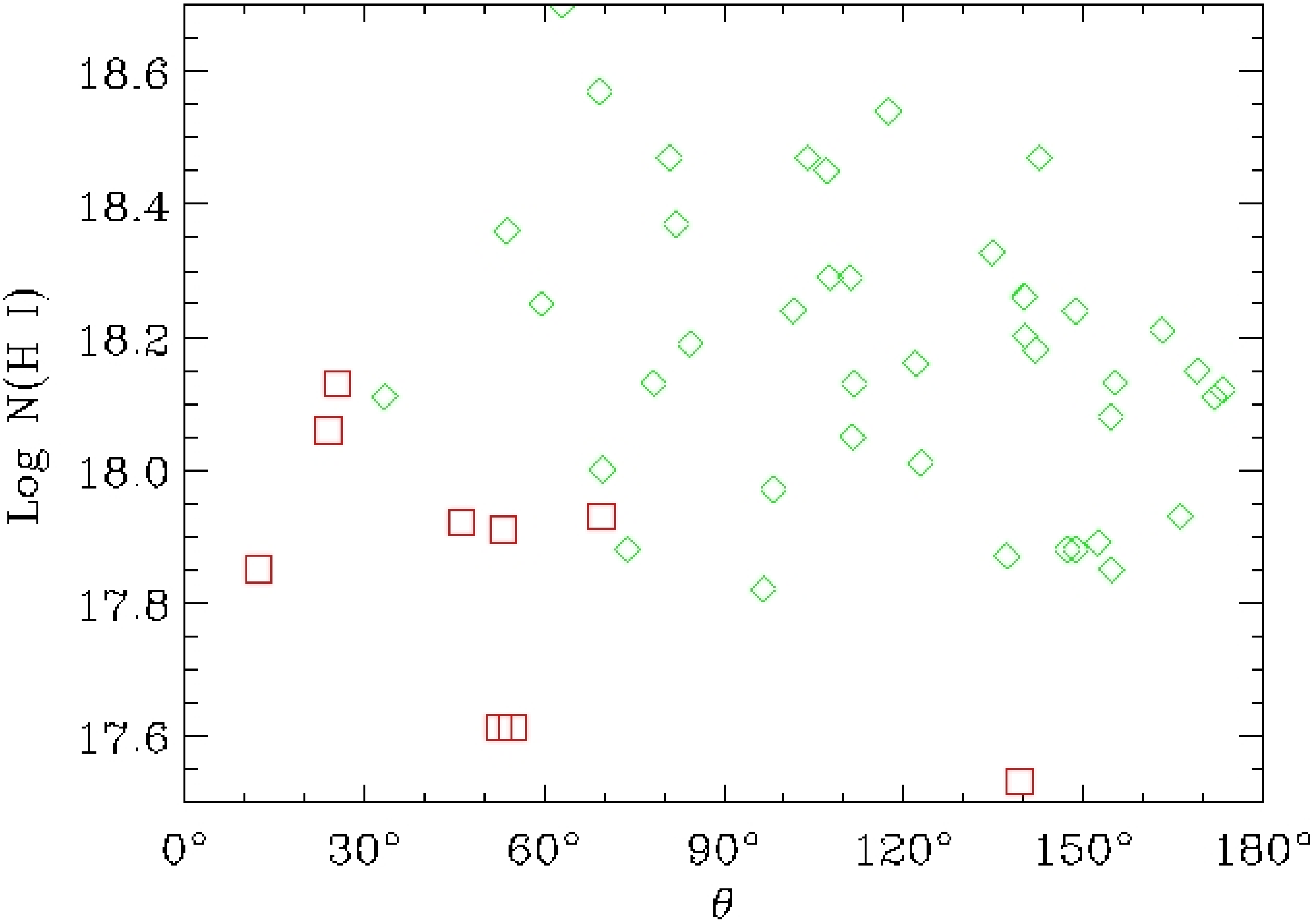
But unfortunately we cannot detect the astrosphere of a Sun-like star like this!



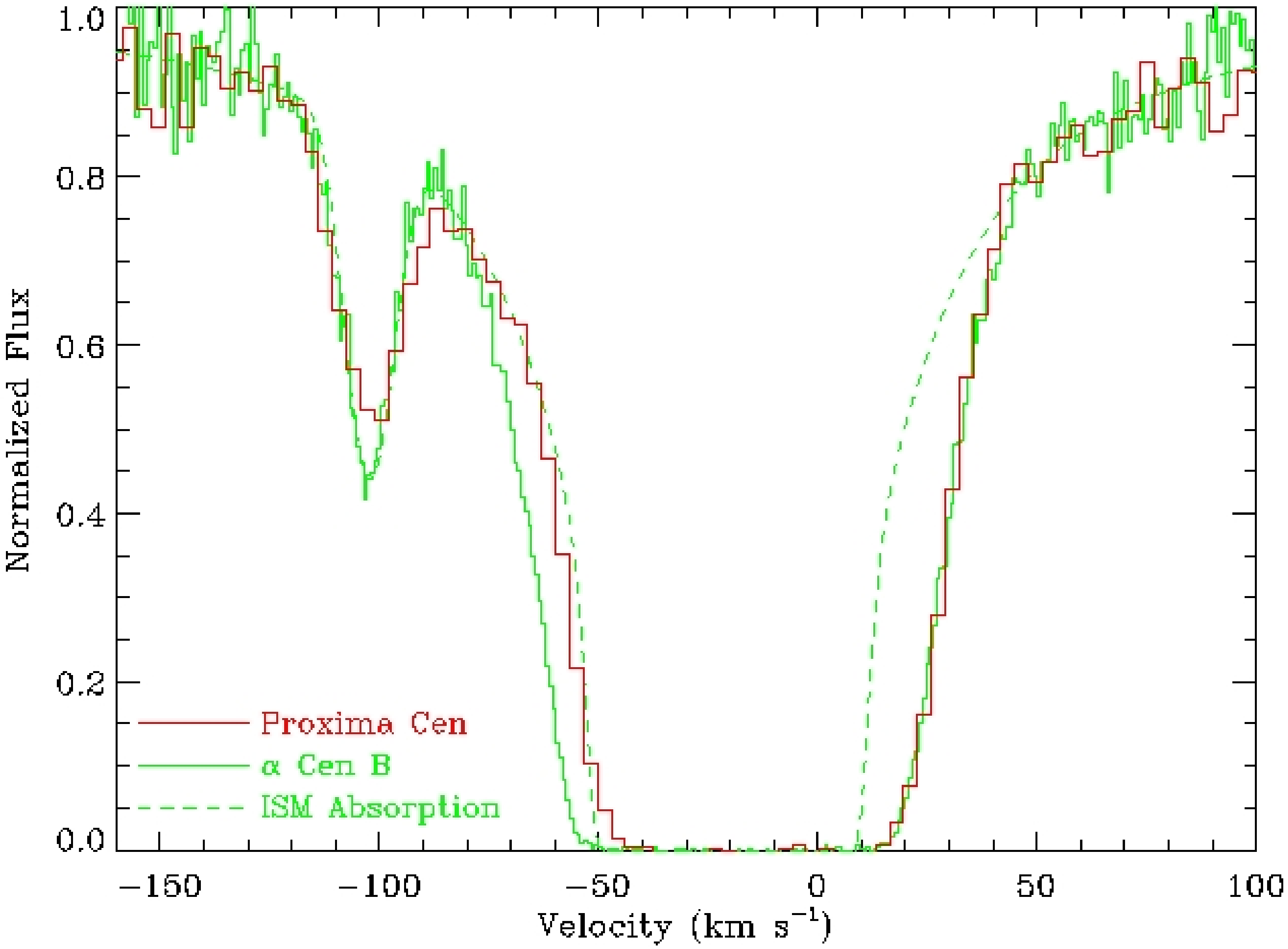
astrospheric absorption

heliospheric absorption

Detectability of Heliospheric Lyα Absorption



Wood et al. 2005, ApJS, 159, 118


Normalized Flux
1.0
0.8
0.6
0.4
0.2
0.0
−150
−100
−50
0
50
100
Velocity (km s^{-1})
Proxima Cen
α Cen B
ISM Absorption

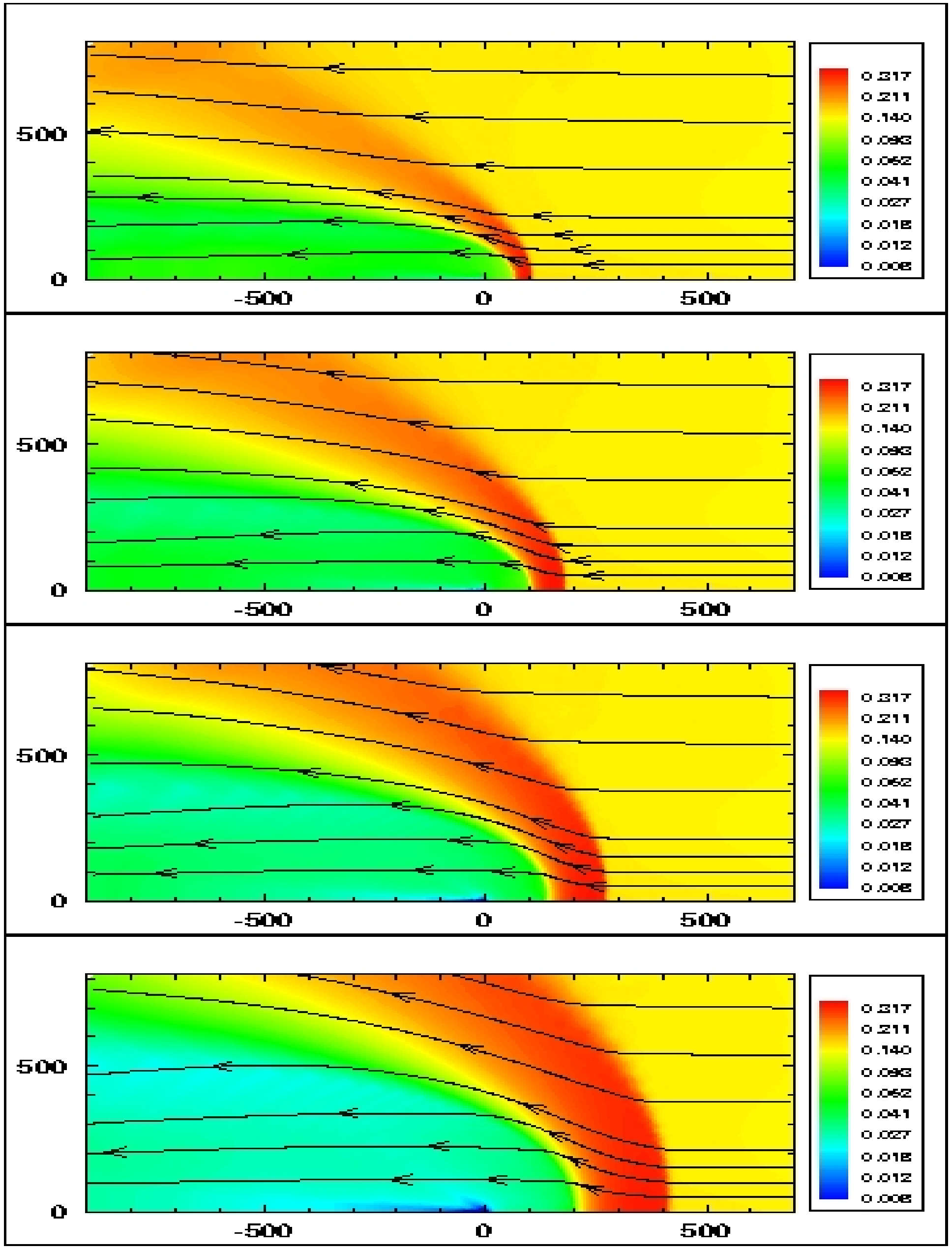
Models of the α Cen Astrosphere

$\dot{M}=0.2\,\dot{M}_\odot$

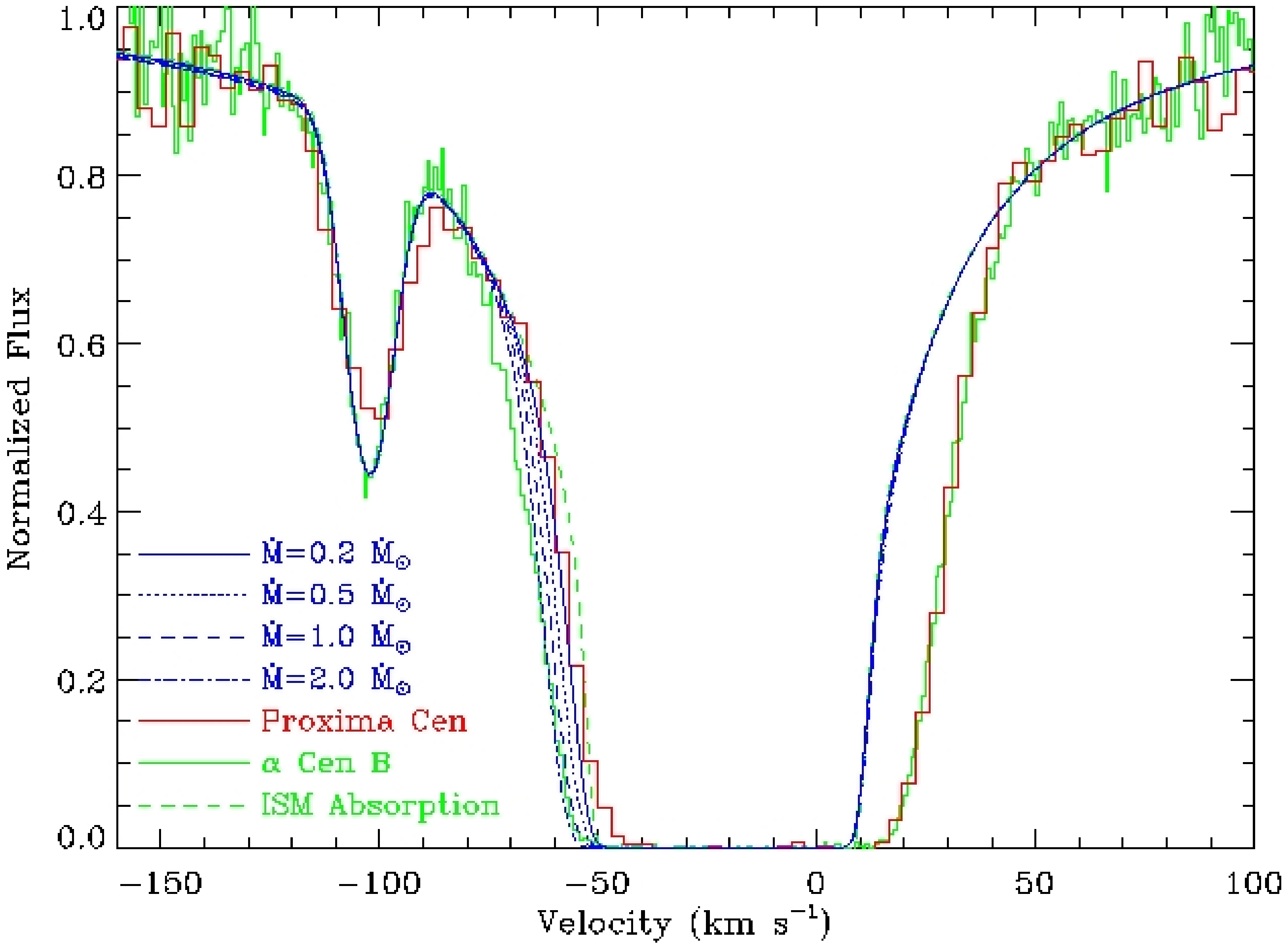
$\dot{M}=0.5\,\dot{M}_\odot$

$\dot{M}=1.0\,\dot{M}_\odot$

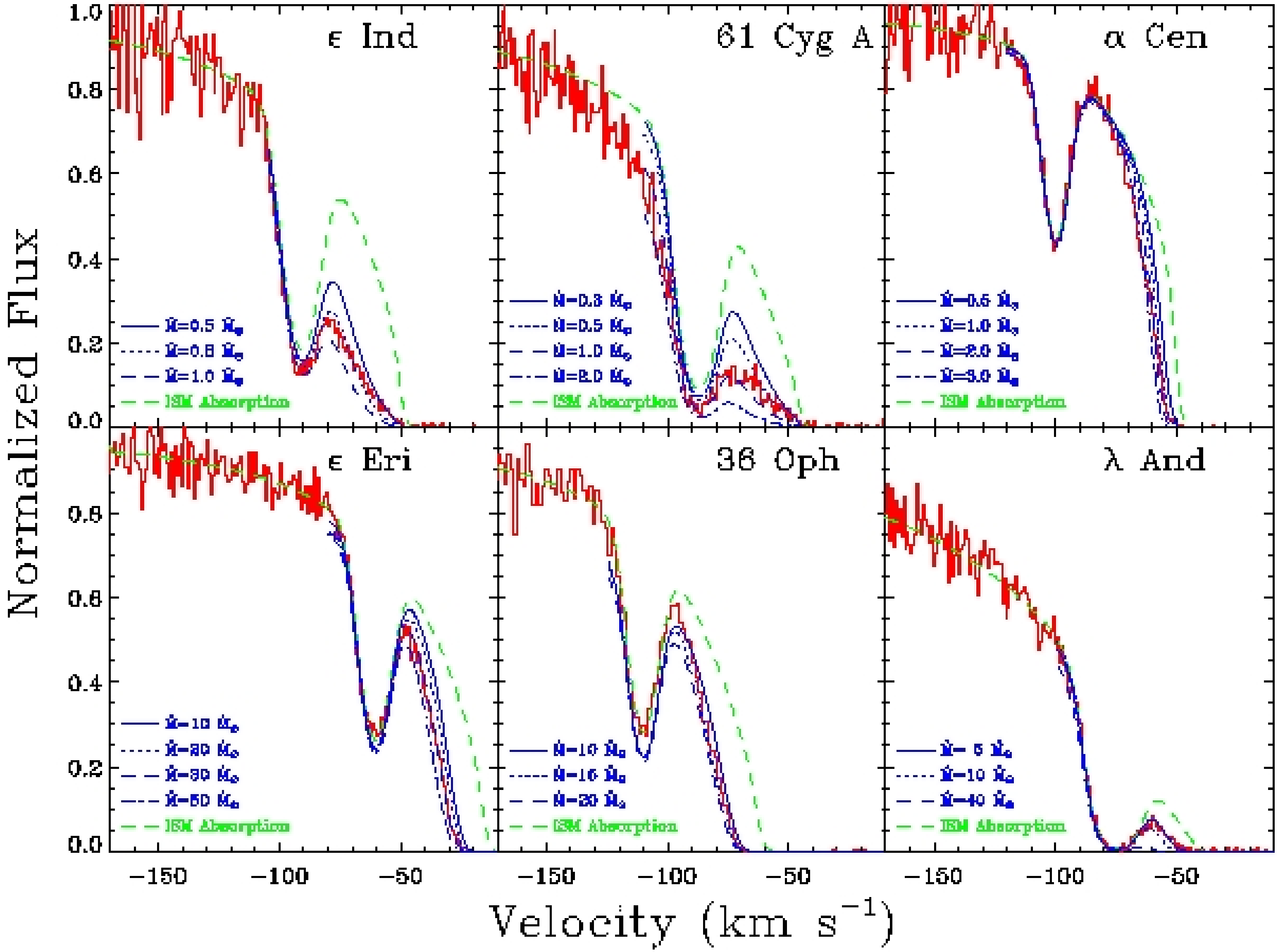
$\dot{M}=2.0\,\dot{M}_\odot$



Astrospheric Absorption Predictions for α Cen

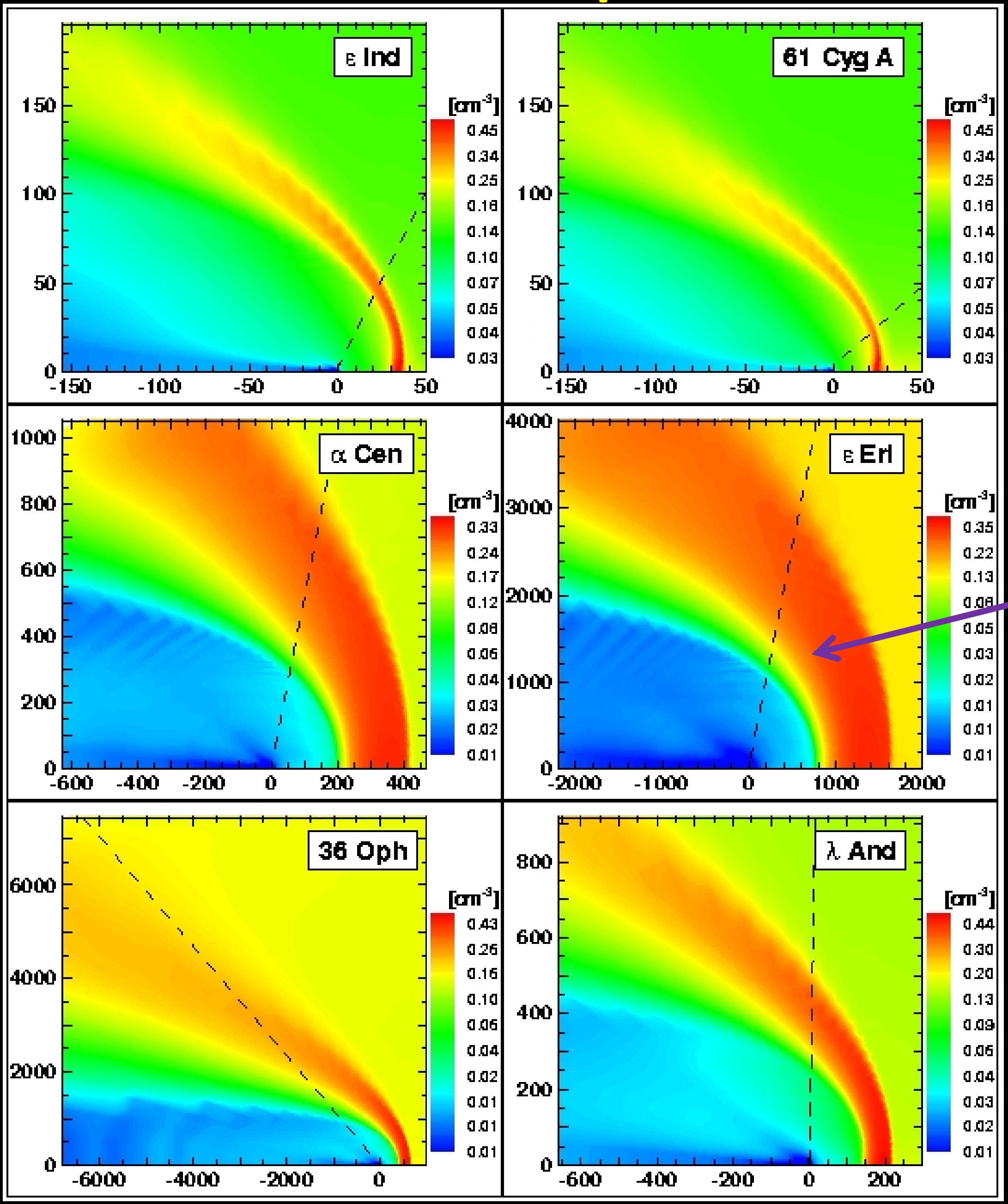


Wood et al. 2001, ApJ, 547, L49



Wood et al. 2002, ApJ, 574, 412

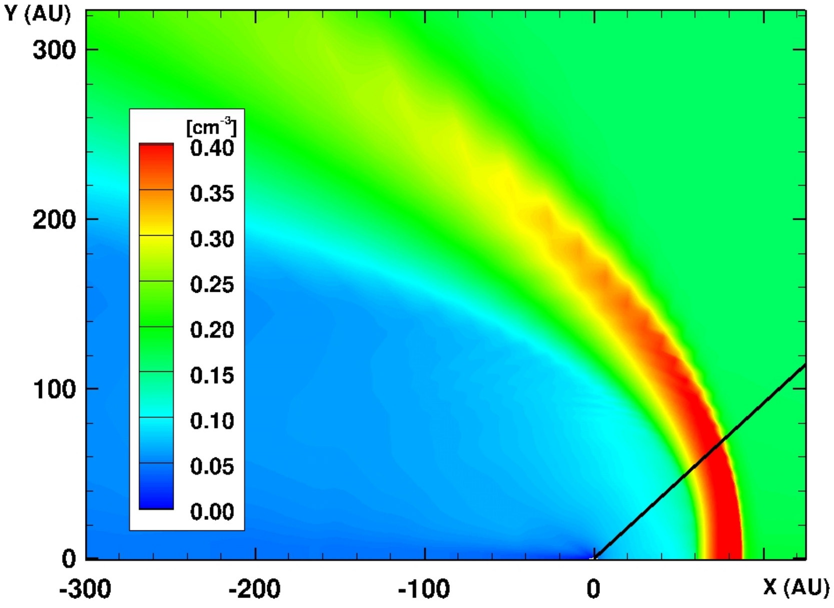
Astrospheric Models

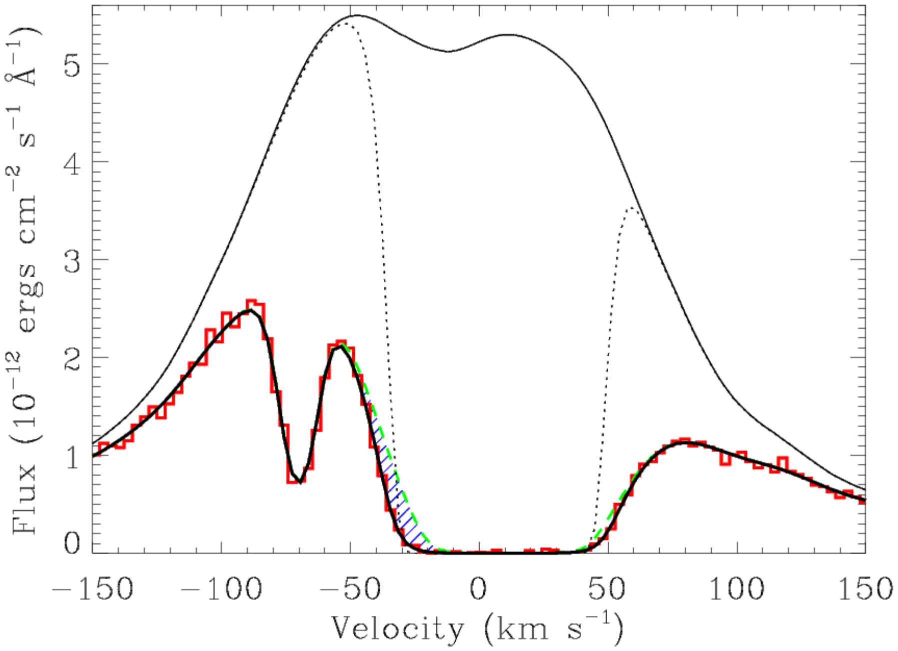


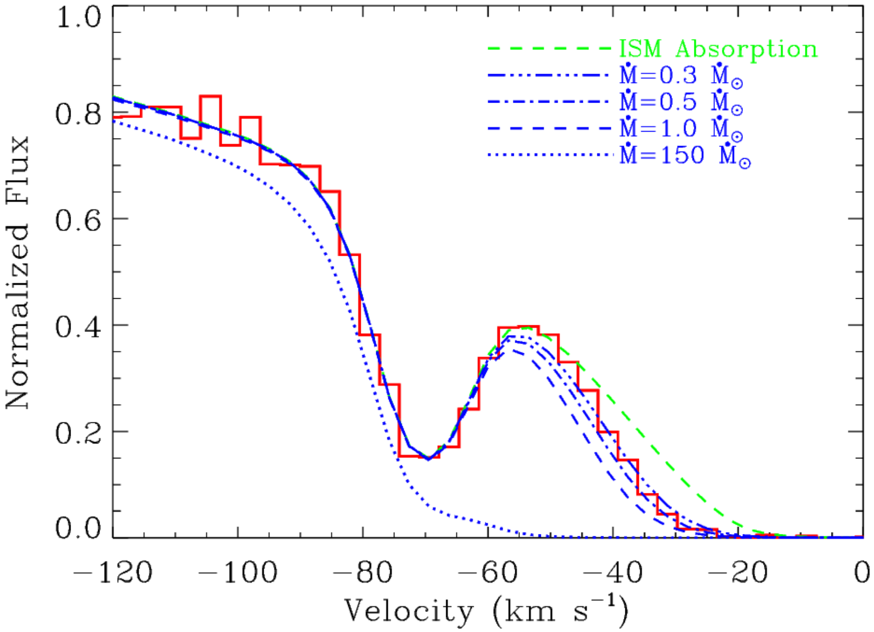
The ε Eri astrosphere is comparable in size to the full moon in the night sky!

The Case of π^1 UMa

- π^1 UMa (G1.5 V) is a 500 Myr solar analog.
- **$\dot{M}<2500\ \dot{M}_{\odot}$** based on 12.2 hr VLA observation (Gaidos et al. 2000, GRL, 27, 501).
- **$\dot{M}\approx 150\ \dot{M}_{\odot}$** from CMEs alone based on extrapolating solar flare-energy/CME-mass relation to young, frequently flaring stars (Drake et al. 2013, ApJ, 764, 170).
- **$\dot{M}\approx 0.5\ \dot{M}_{\odot}$** based on astrospheric absorption (Wood et al. 2014, ApJ, 781, L33).
- Could a very long observation by EVLA or ALMA reduce the radio upper limit significantly?







List of Astrospheric Measurements

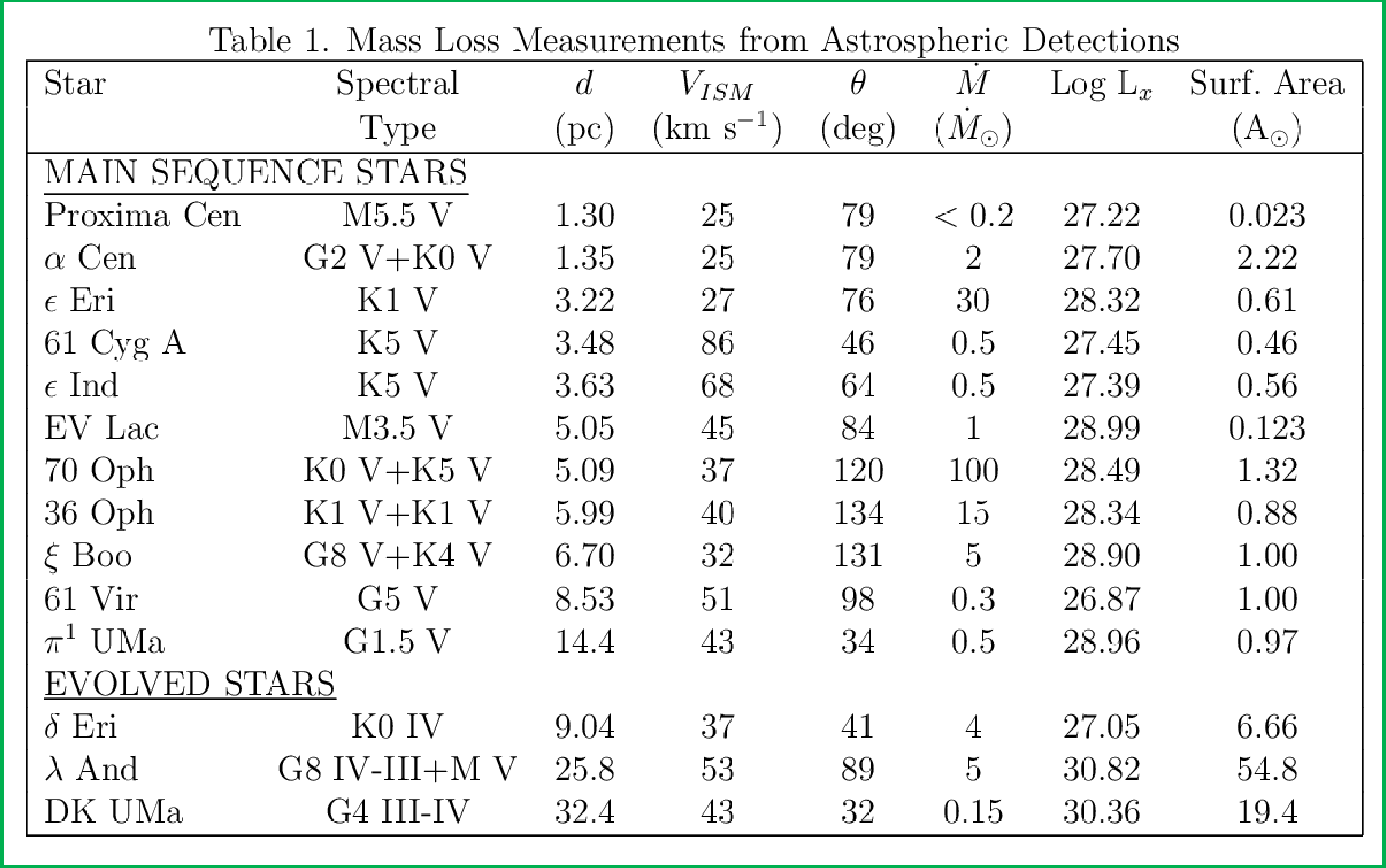
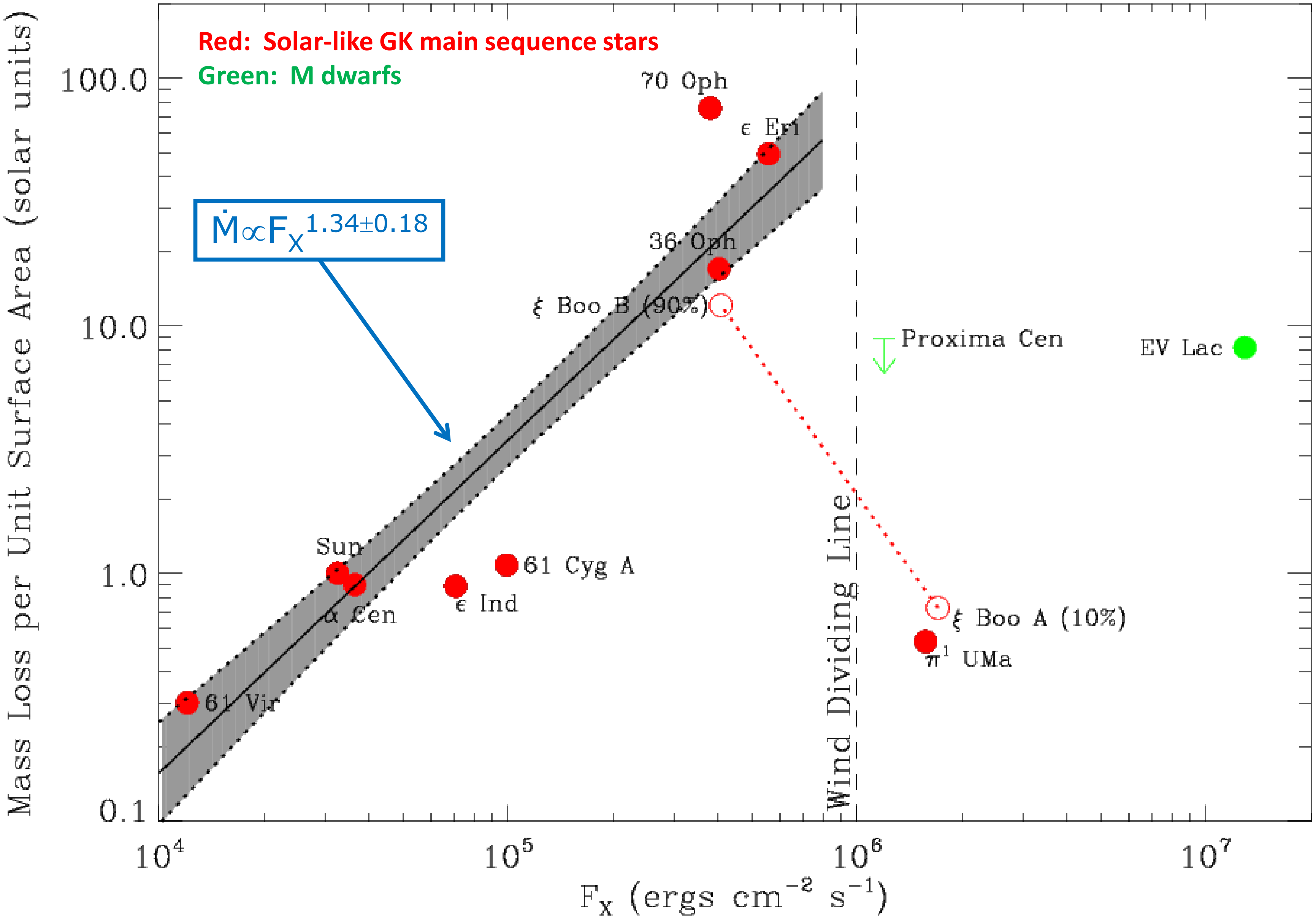


Table 1. Mass Loss Measurements from Astrospheric Detections

Star	Spectral Type	d (pc)	V_{ISM} (km s^{-1})	θ (deg)	$\dot{M}$ ($\dot{M}_\odot$)	Log L_x	Surf. Area ($A_\odot$)
MAIN SEQUENCE STARS							
Proxima Cen	M5.5 V	1.30	25	79	< 0.2	27.22	0.023
α Cen	G2 V+K0 V	1.35	25	79	2	27.70	2.22
ϵ Eri	K1 V	3.22	27	76	30	28.32	0.61
61 Cyg A	K5 V	3.48	86	46	0.5	27.45	0.46
ϵ Ind	K5 V	3.63	68	64	0.5	27.39	0.56
EV Lac	M3.5 V	5.05	45	84	1	28.99	0.123
70 Oph	K0 V+K5 V	5.09	37	120	100	28.49	1.32
36 Oph	K1 V+K1 V	5.99	40	134	15	28.34	0.88
ξ Boo	G8 V+K4 V	6.70	32	131	5	28.90	1.00
61 Vir	G5 V	8.53	51	98	0.3	26.87	1.00
π^1 UMa	G1.5 V	14.4	43	34	0.5	28.96	0.97
EVOLVED STARS							
δ Eri	K0 IV	9.04	37	41	4	27.05	6.66
λ And	G8 IV-III+M V	25.8	53	89	5	30.82	54.8
DK UMa	G4 III-IV	32.4	43	32	0.15	30.36	19.4

Mass Loss/X-ray Relation



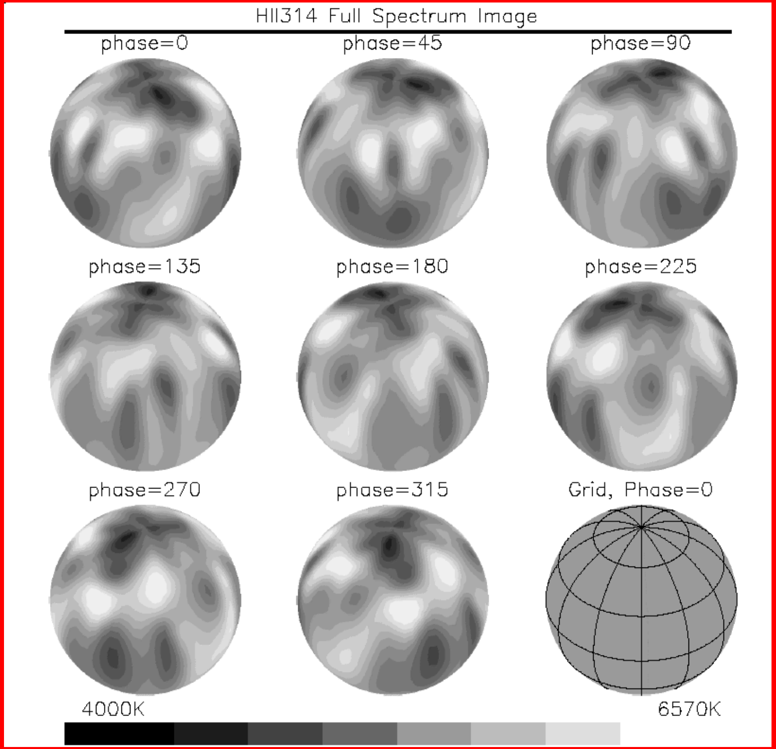
Red: Solar-like GK main sequence stars

Green: M dwarfs

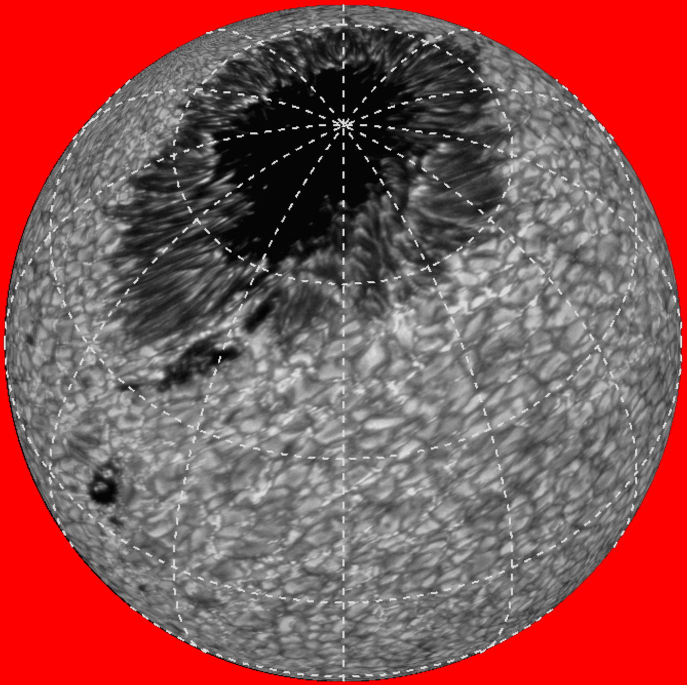
$\dot{M} \propto F_X^{1.34 \pm 0.18}$

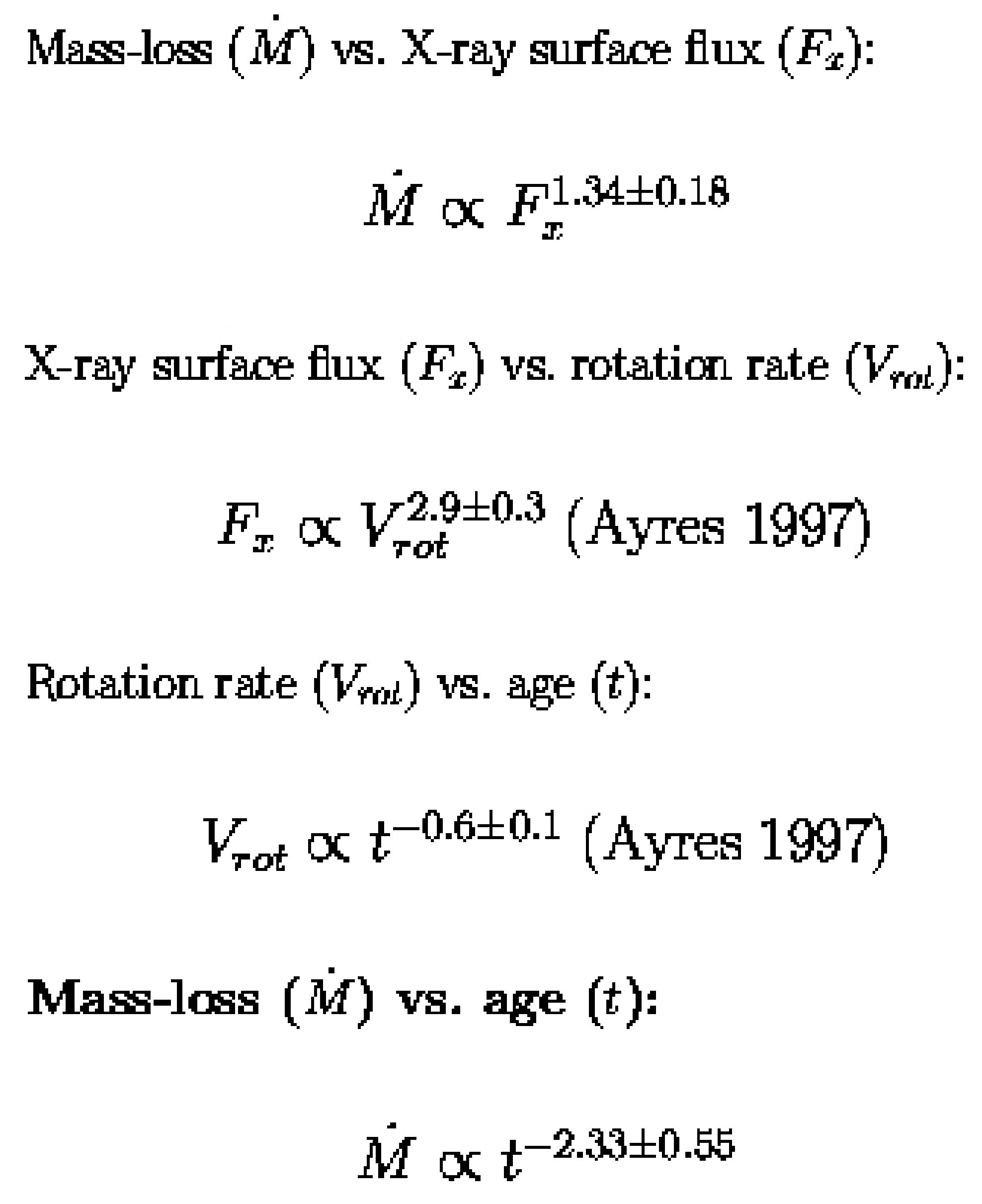
Wood et al. 2014, ApJ, 781, L33

Is Magnetic Topology Inhibiting the Winds of Young, Active Stars?



Rice & Strassmeier 2001, A&A, 377, 264





Mass-loss ($\dot{M}$) vs. X-ray surface flux (F_x):

$$\dot{M} \propto F_x^{1.34\pm0.18}$$

X-ray surface flux (F_x) vs. rotation rate (V_{rot}):

$$F_x \propto V_{rot}^{2.9\pm0.3} \text{ (Ayres 1997)}$$

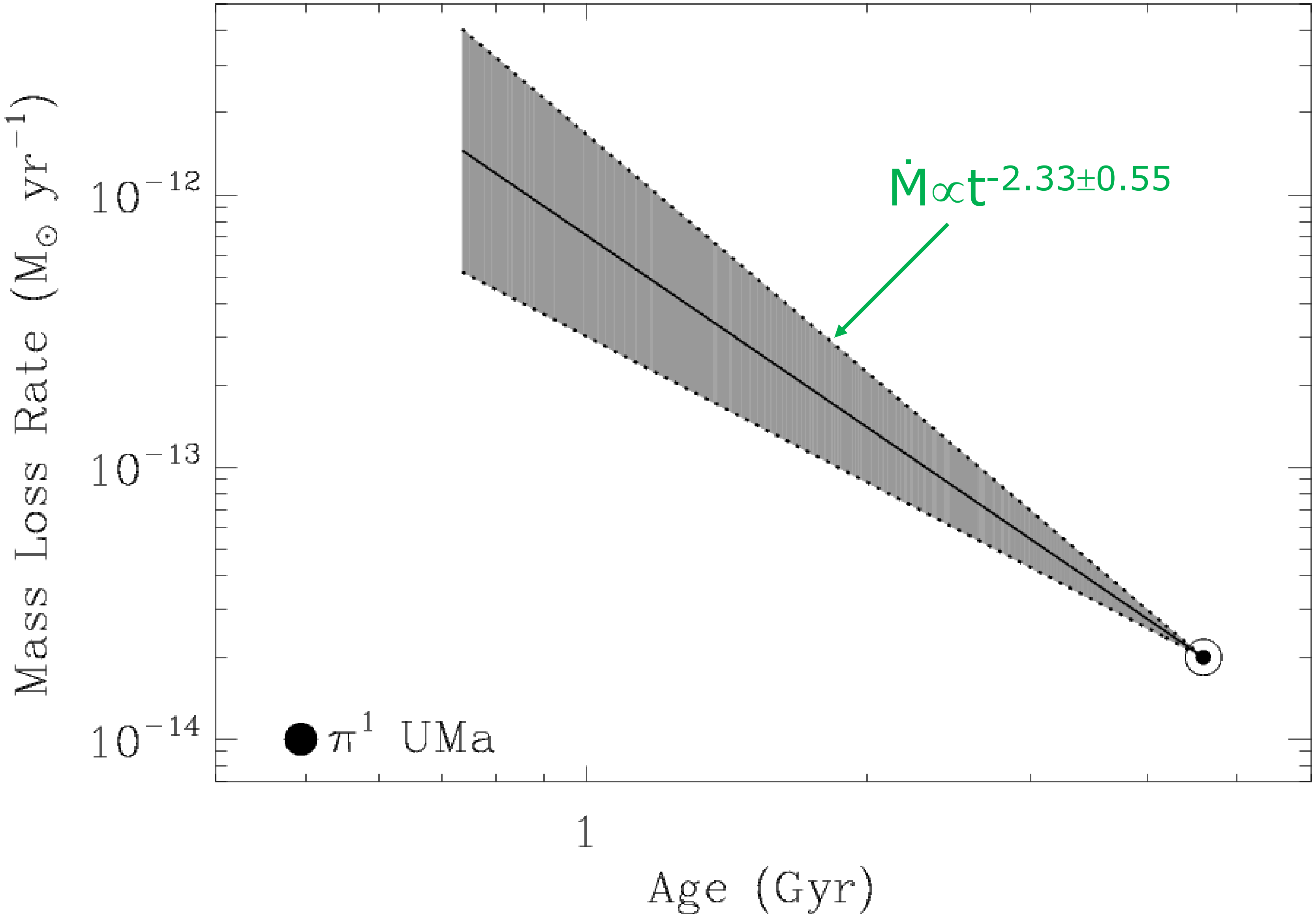
Rotation rate (V_{rot}) vs. age (t):

$$V_{rot} \propto t^{-0.6\pm0.1} \text{ (Ayres 1997)}$$

Mass-loss ($\dot{M}$) vs. age (t):

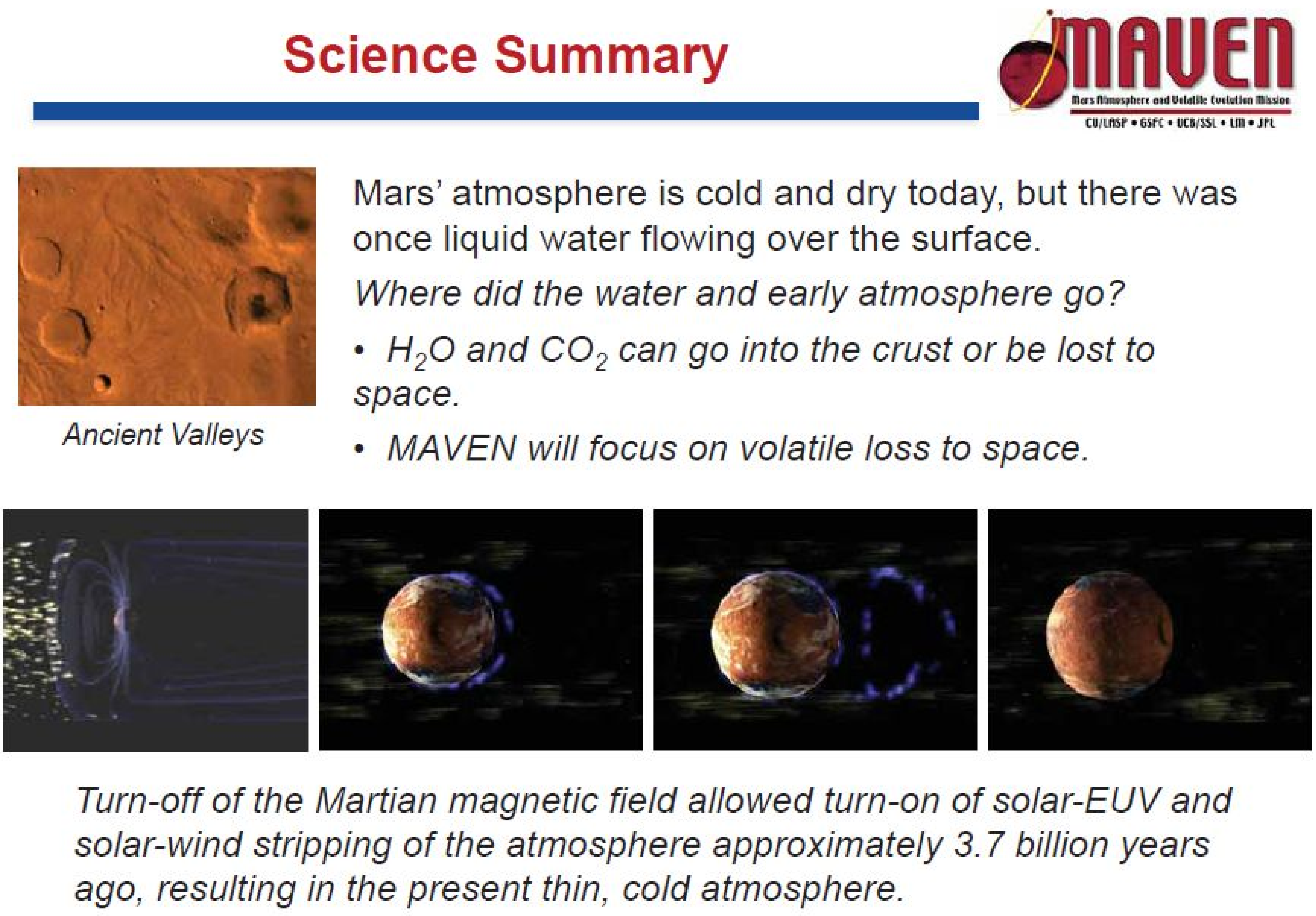
$$\dot{M} \propto t^{-2.33\pm0.55}$$

Wind Evolution for a Sun-like Star



Evolution of the Martian Atmosphere

MAVEN now at Mars!



Science Summary

Ancient Valleys

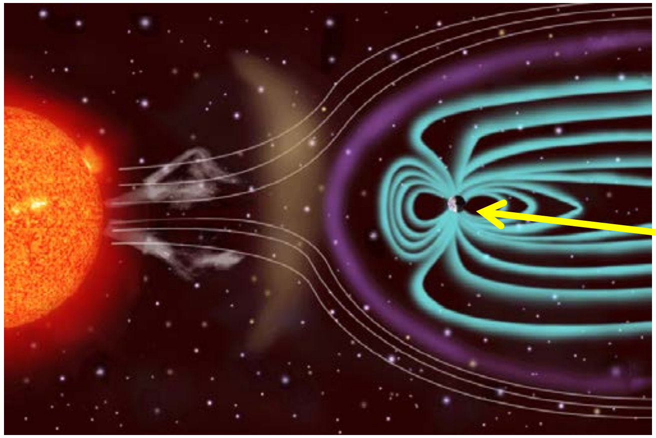
Mars' atmosphere is cold and dry today, but there was once liquid water flowing over the surface.

Where did the water and early atmosphere go?

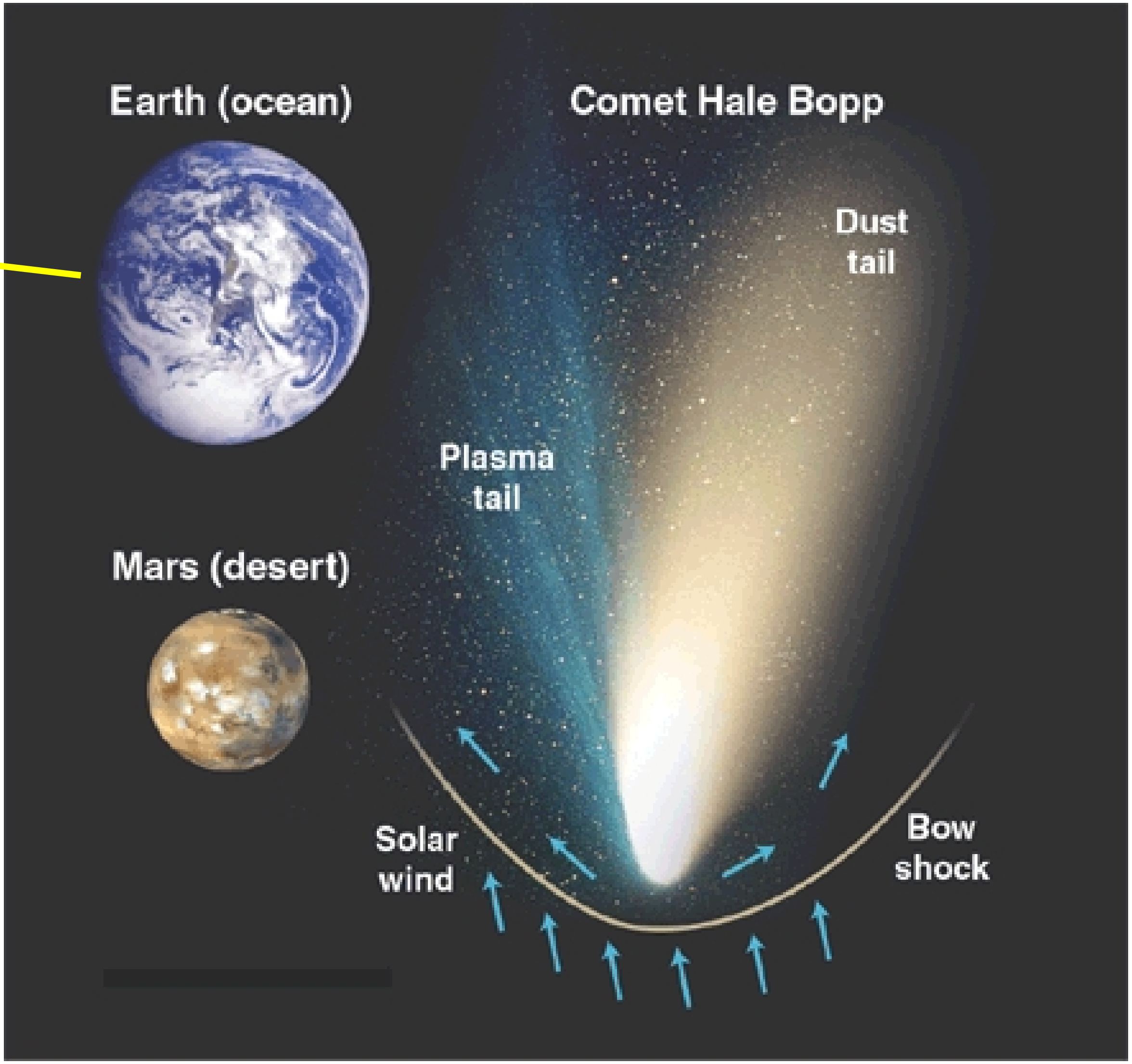
- *H_2O and CO_2 can go into the crust or be lost to space.*
- *MAVEN will focus on volatile loss to space.*

Turn-off of the Martian magnetic field allowed turn-on of solar-EUV and solar-wind stripping of the atmosphere approximately 3.7 billion years ago, resulting in the present thin, cold atmosphere.

What Role do Magnetospheres Play in Atmospheric Evolution?

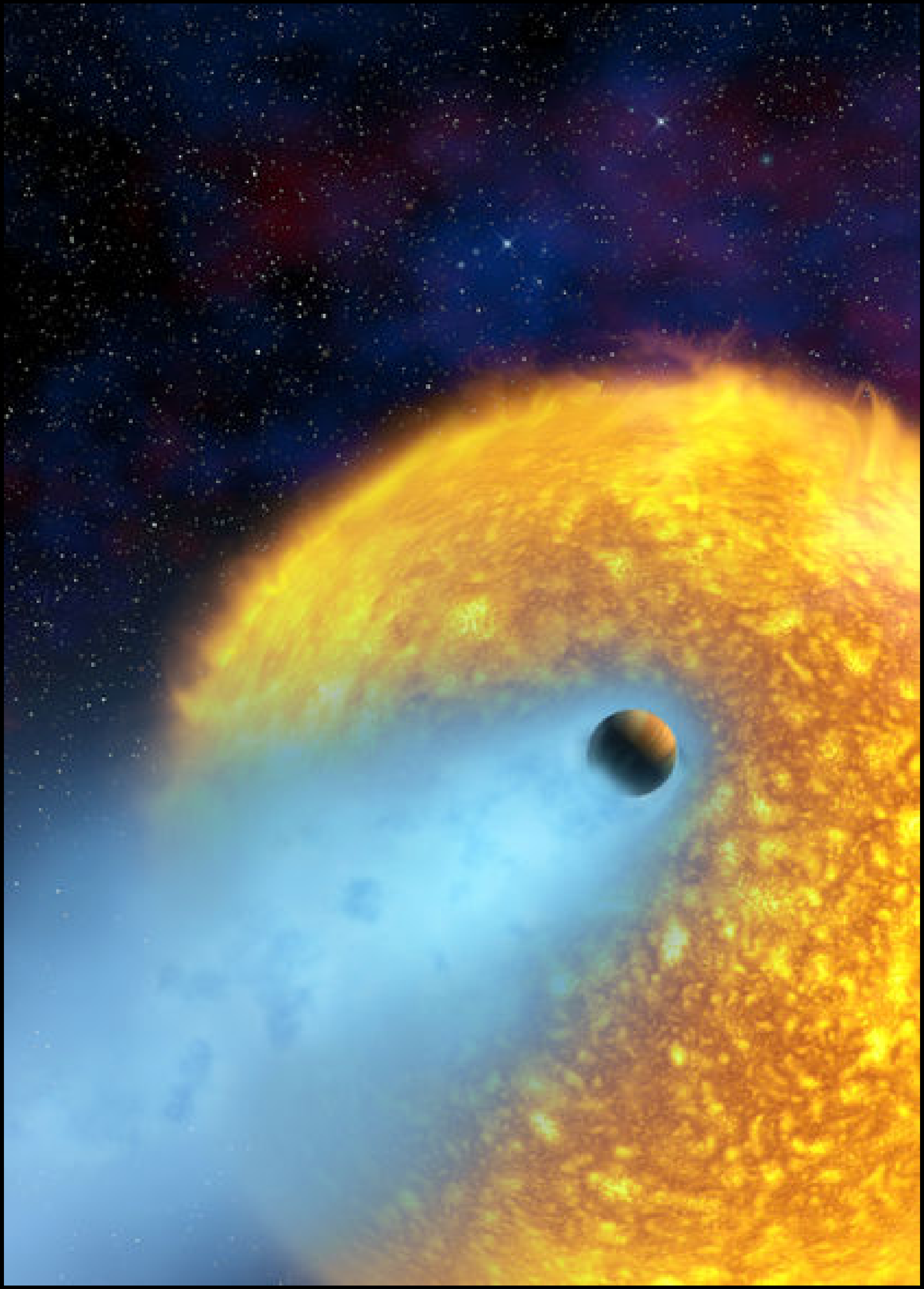


Earth is protected by a "magnetosphere," but Mars is not!



Lundin 2001, Science, 291, 1909

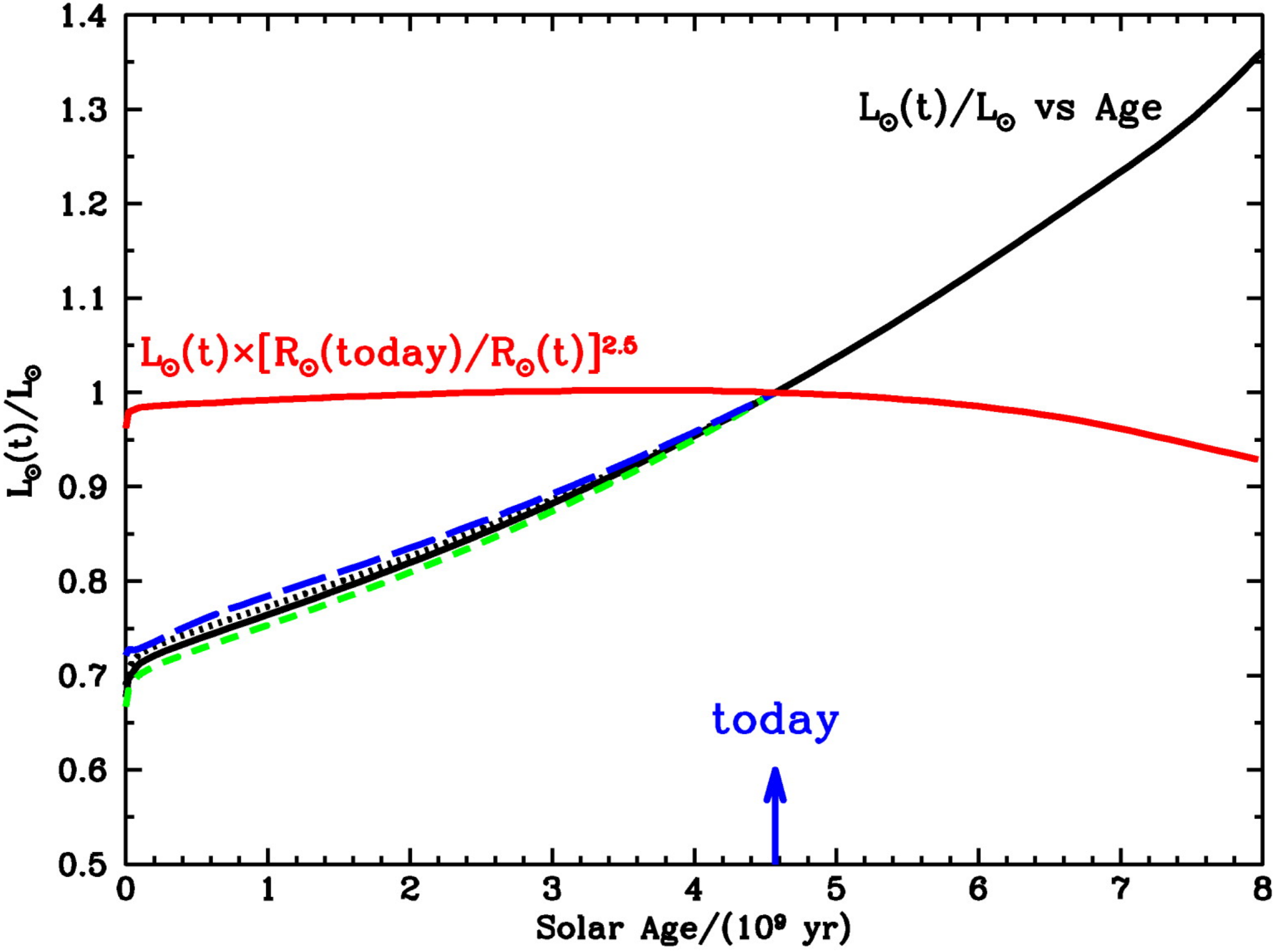
Stellar Wind Erosion of a “Hot Jupiter”



This is just an artist’s conception of a stellar wind eroding a planetary atmosphere, but Lyα absorption from such an eroding atmosphere may have actually been detected for the transiting exoplanet HD 209458b (Vidal-Madjar et al. 2003, Nature, 422, 143; Linsky et al. 2010, ApJ, 717, 1291).

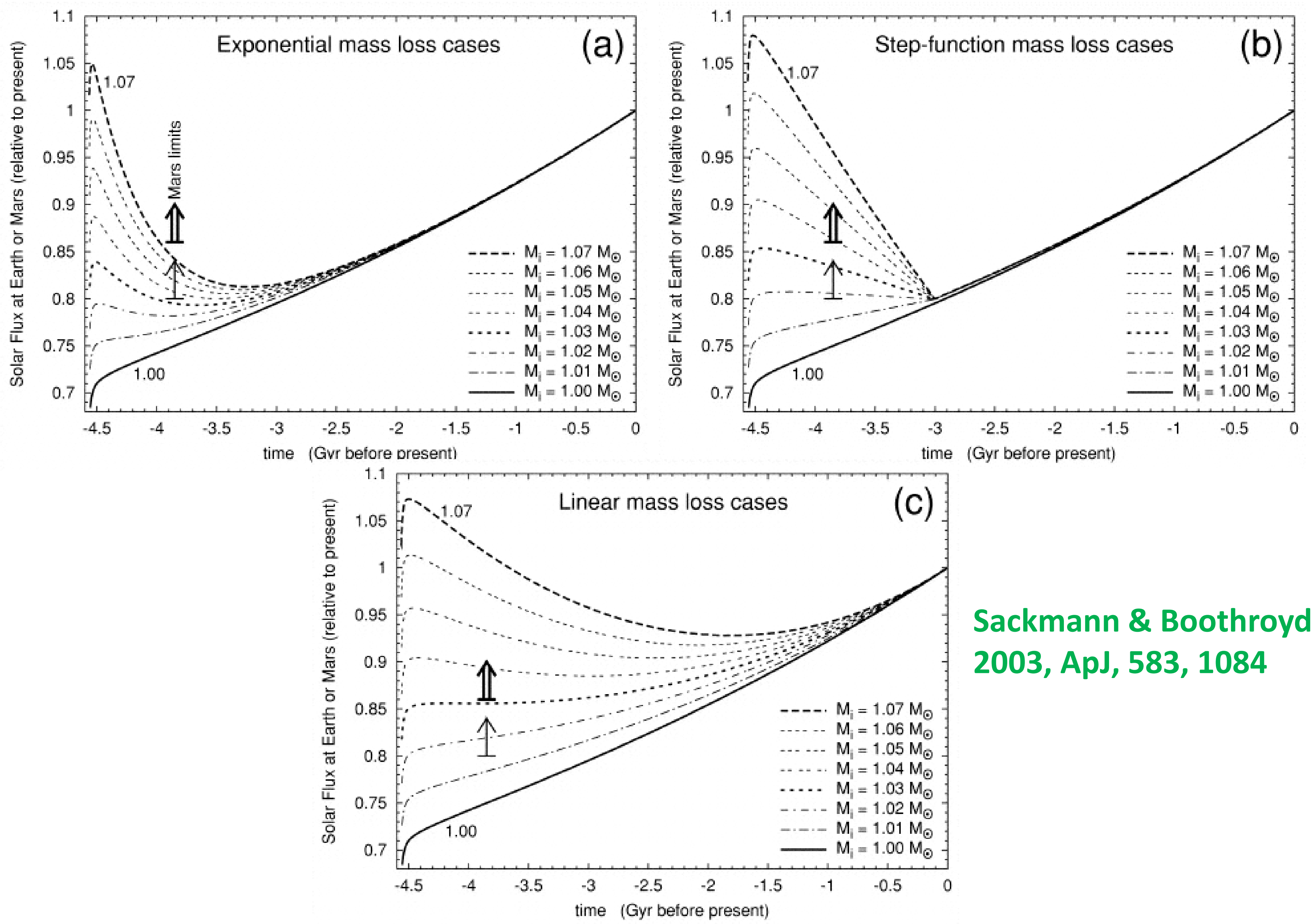
The Faint Young Sun Problem (FYSP)

(first defined by Sagan & Mullen 1972, Science, 177, 52)



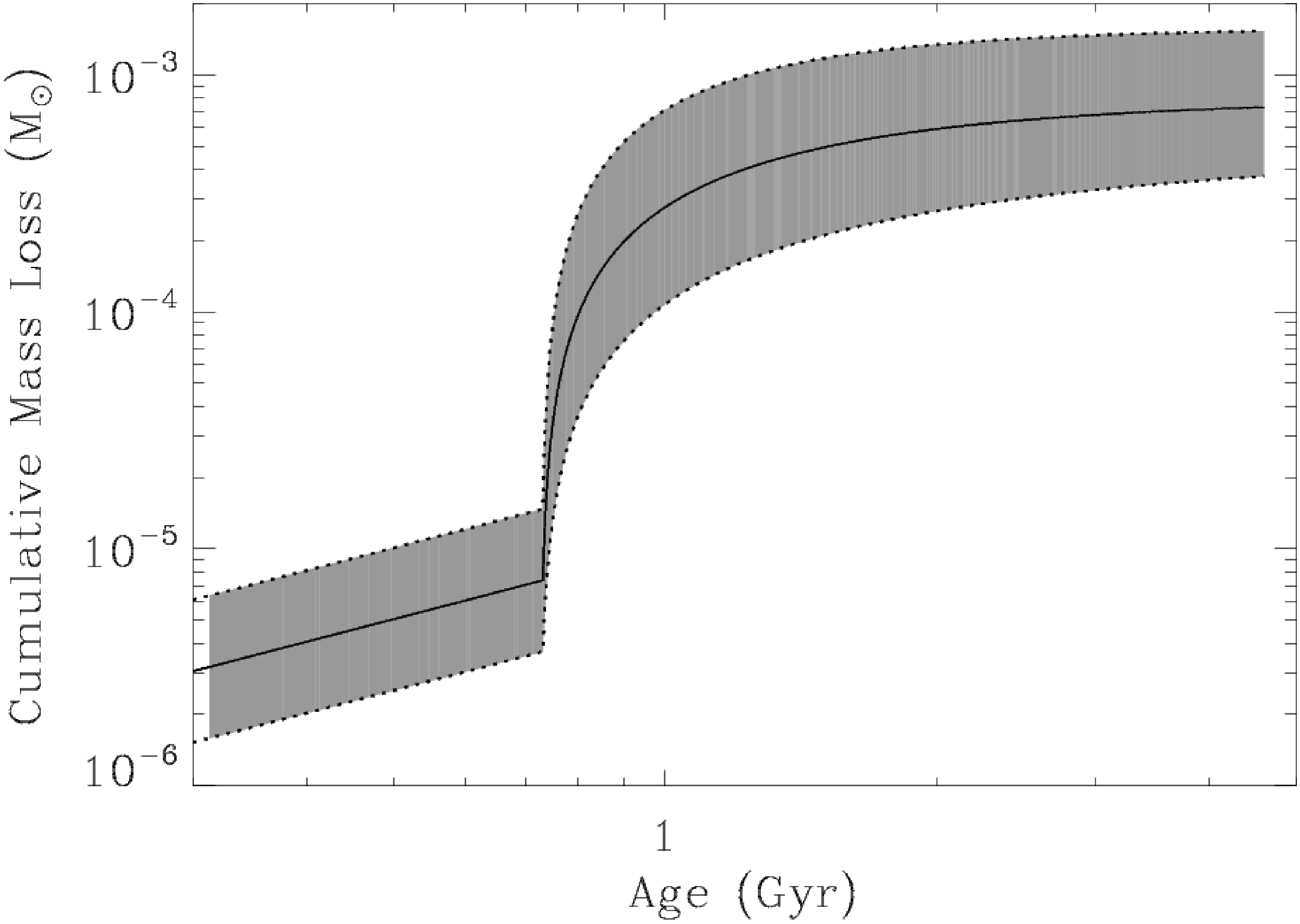
Bahcall et al. 2001, ApJ, 555, 990

Could the FYSP be Resolved by a More Massive Young Sun?

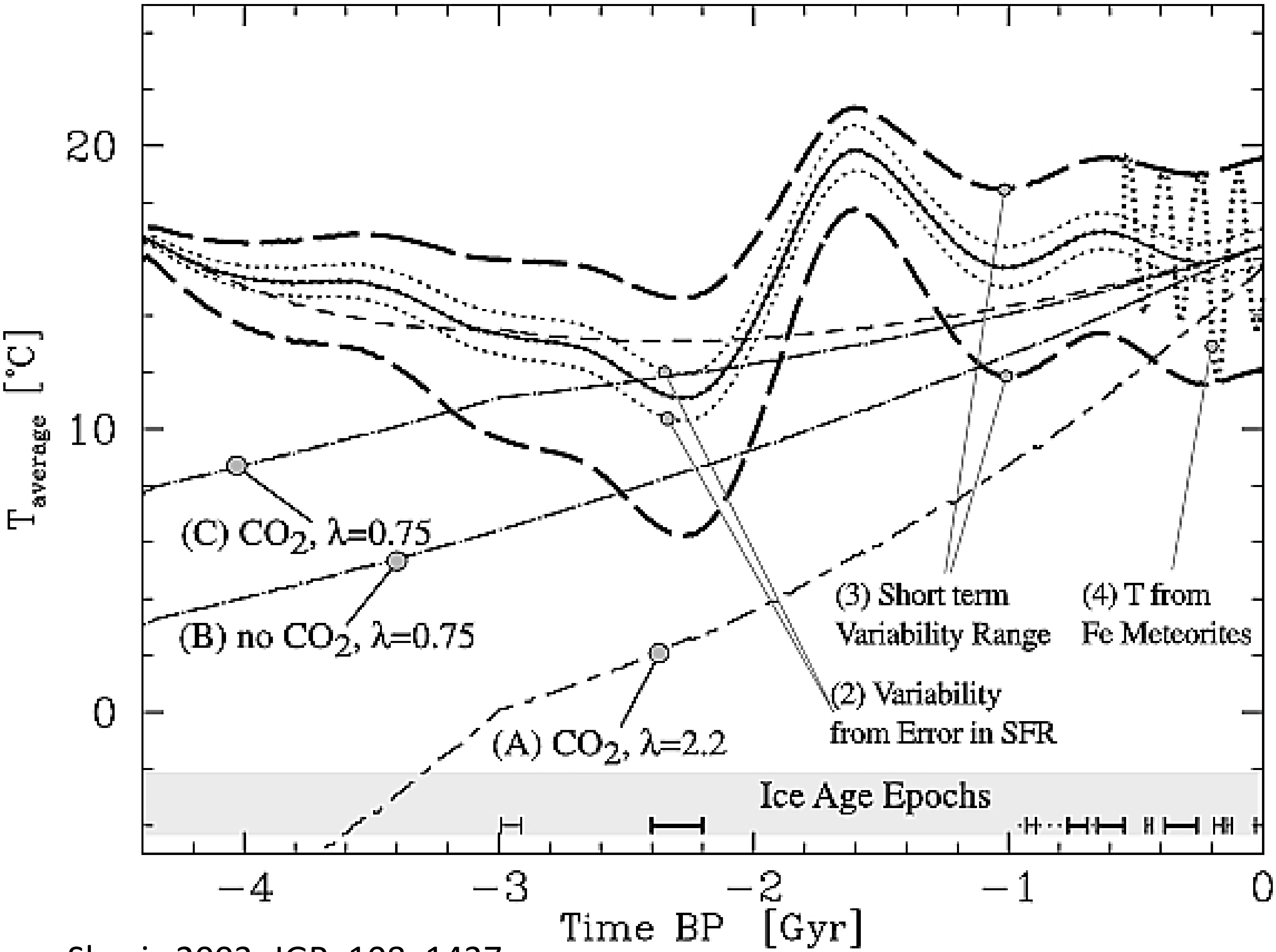


Sackmann & Boothroyd 2003, ApJ, 583, 1084

Mass Lost due to Solar Wind Inferred from Astrospheric Measurements



Could a Stronger Wind for the Young Sun Explain the FYSP Via Cosmic Ray Cooling?



Shaviv 2003, JGR, 108, 1437

SUMMARY

- Currently the only way to study the astrospheres and winds of solar-like stars is through astrospheric Lyα absorption observed by HST.
- Analysis of the astrospheric absorption suggests that for solar-like GK dwarfs, mass loss and activity are correlated such that $\dot{M} \propto F_X^{1.34\pm0.18}$.
- However, this relation does not extend to high activity levels ($F_X > 10^6$ ergs cm^{-2} s^{-1}), possibly indicating a fundamental change in magnetic structure for more active stars.
- The mass-loss/activity relation described above suggests that mass loss decreases with time as $\dot{M} \propto t^{-2.33\pm0.55}$. However, the apparent high activity cutoff means that this mass loss evolution law doesn't extend to times earlier than t~0.7 Gyr.
- Despite the higher mass loss rates predicted for the young Sun by our mass loss evolution law, the total mass lost by the Sun in its lifetime is still insignificant, so this stronger young wind can't directly solve the Faint Young Sun problem, though there is speculation that it could indirectly via cosmic ray attenuation.
- The existence of generally stronger winds at younger stellar ages makes it more likely that solar/stellar wind erosion plays an important role in the evolution of planetary atmospheres.