Observational Constraints on Stellar Winds from the Hubble Space Telescope

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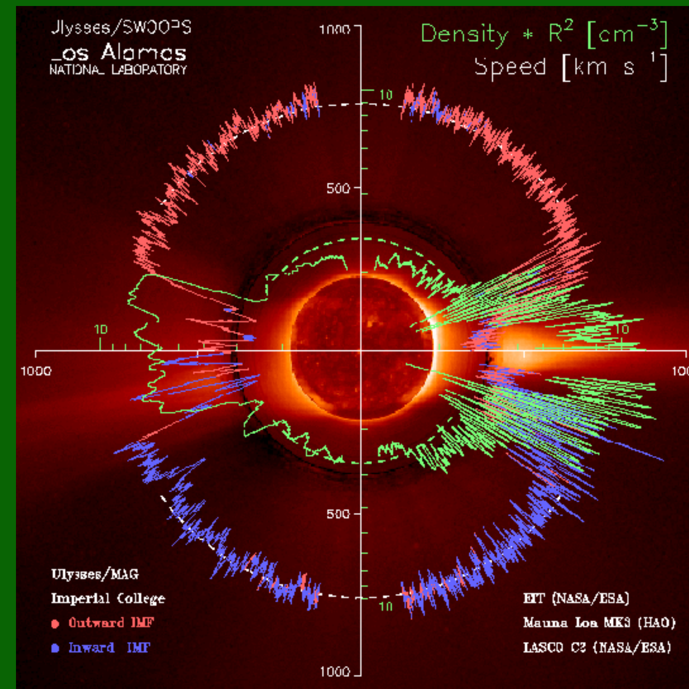
Movie from LASCO/C3 coronagraph on SOHO spacecraft

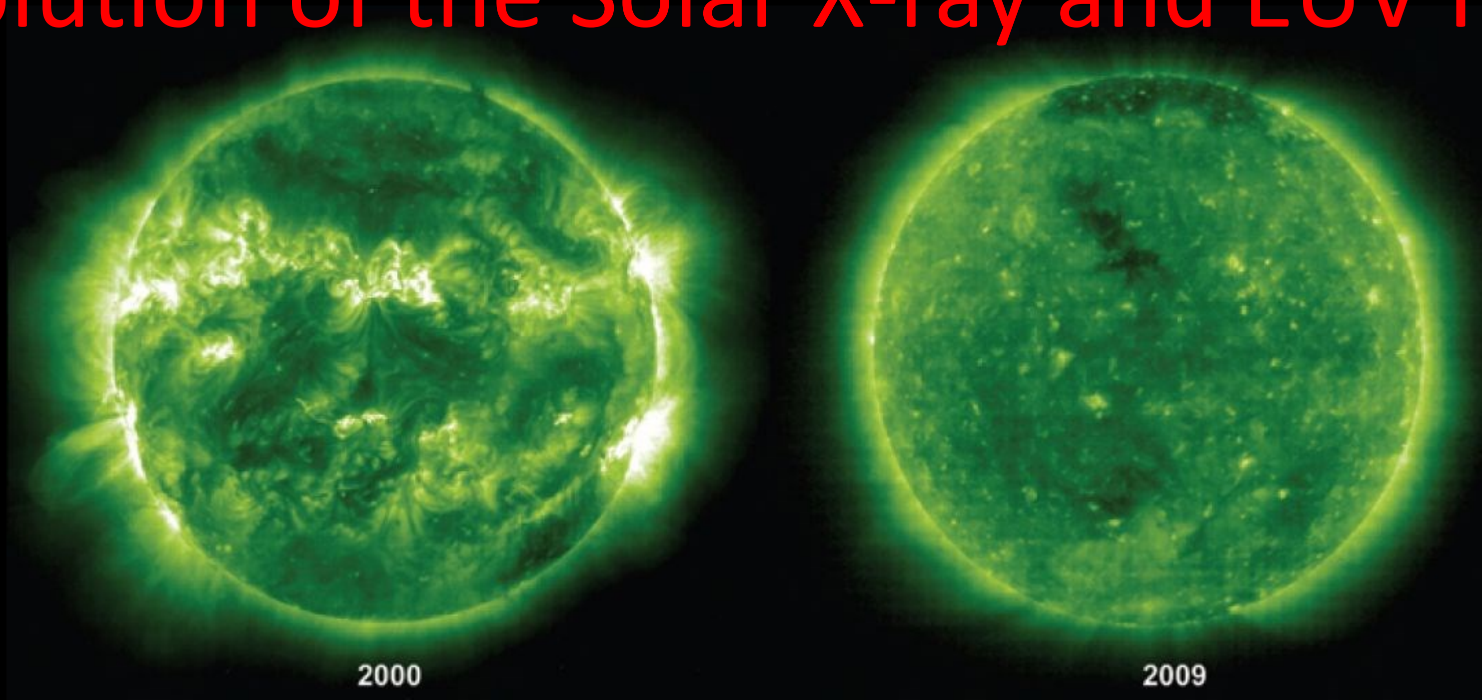


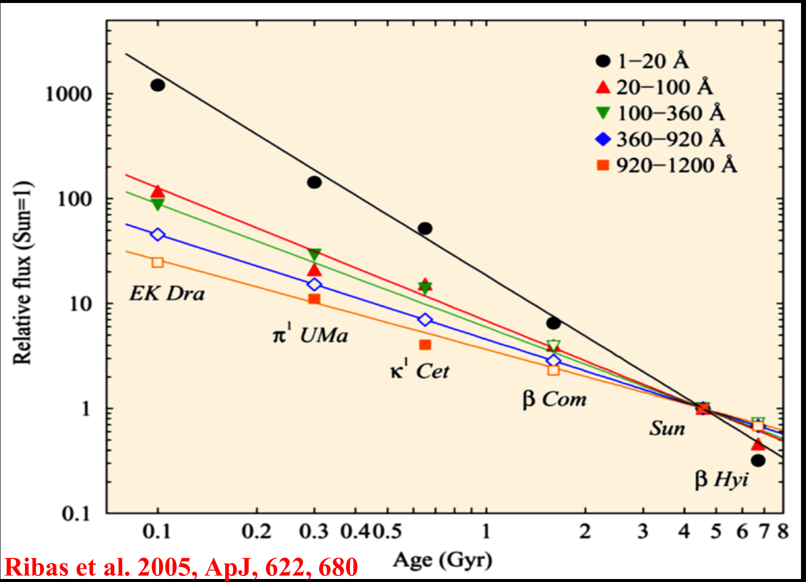
Property (1 AU)	Slow wind	Fast wind
Speed	430 ± 100 km/s	700–900 km/s
Density	$\simeq 10$ cm^{-3}	$\simeq 3$ cm^{-3}
Flux	$(3.5 \pm 2.5) \times 10^8$ cm^{-2}s^{-1}	$(2 \pm 0.5) \times 10^8$ cm^{-2}s^{-1}
Magnetic field	6 ± 3 nT	6 ± 3 nT
Temperatures	$T_p = (4 \pm 2) \times 10^4$ K $T_e = (1.3 \pm 0.5) \times 10^5$ 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

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).

Evolution of the Solar X-ray and EUV FLux

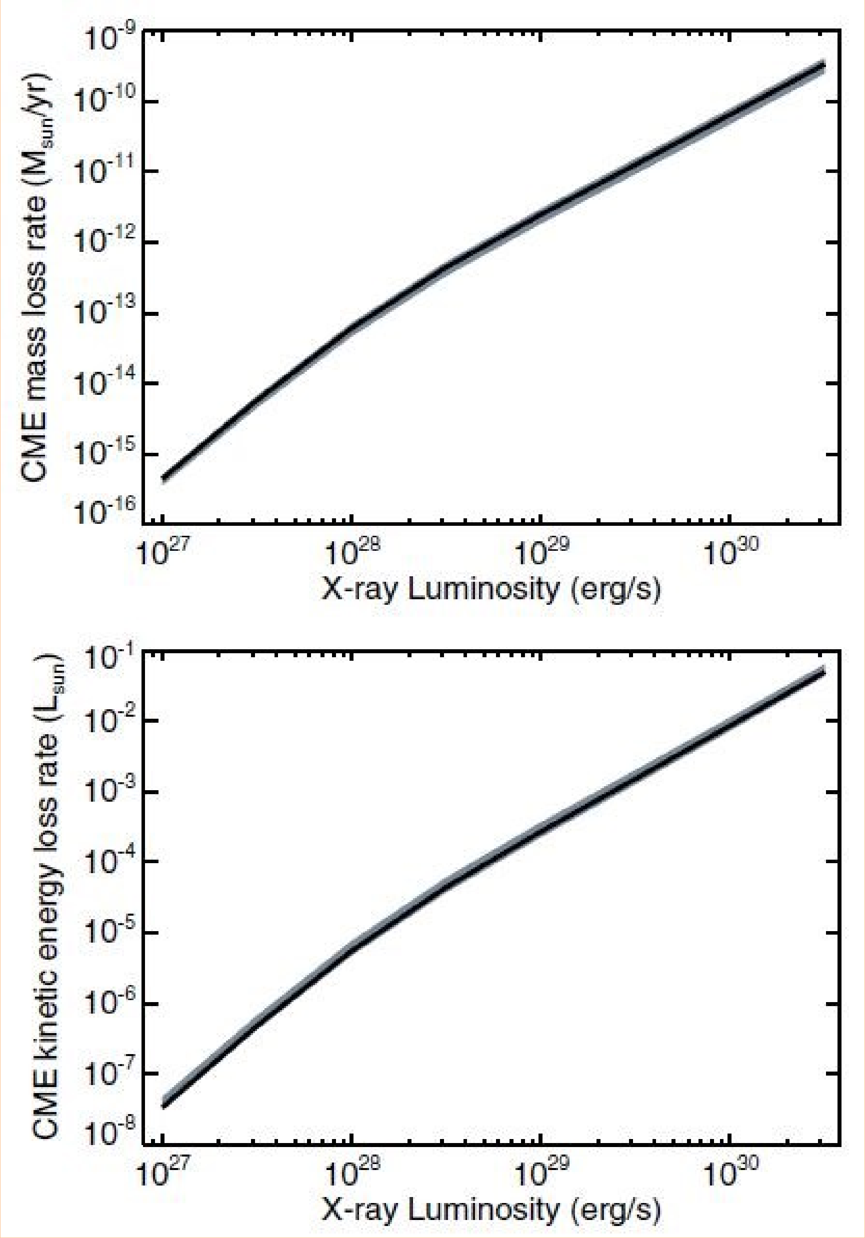




The Case for a Very Strong Wind for the Young Sun

1. The young Sun would have been much more coronally active, with higher coronal densities, so one would intuitively expect a stronger wind.
2. Aside from the quiescent wind, the stronger and more frequent flares of the young Sun should by themselves lead to a massive CME-dominated wind. Example: Due to CMEs alone, Drake et al. (2013) predict $\dot{M}=150\ \dot{M}_\odot$ for the 500 Myr old solar analog π^1 UMa.

Conclusion: There is every reason to believe the solar wind must have been much stronger in the past.



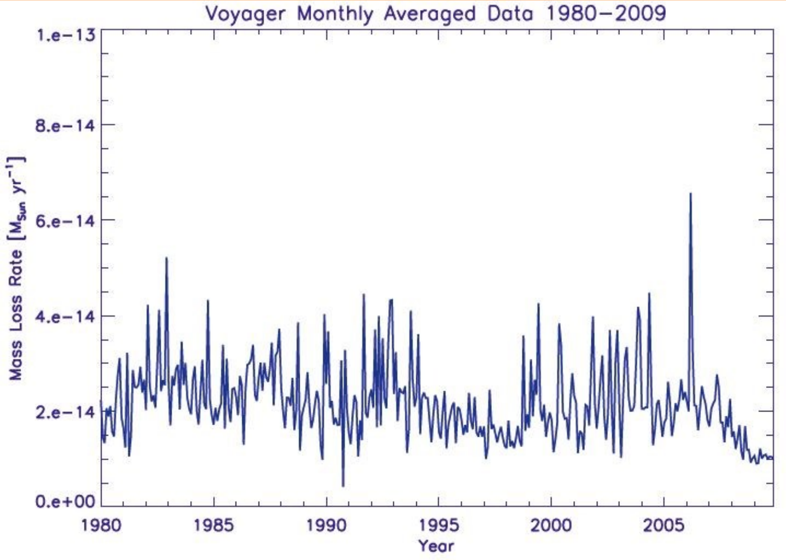
Drake et al. 2013, ApJ, 764, 170

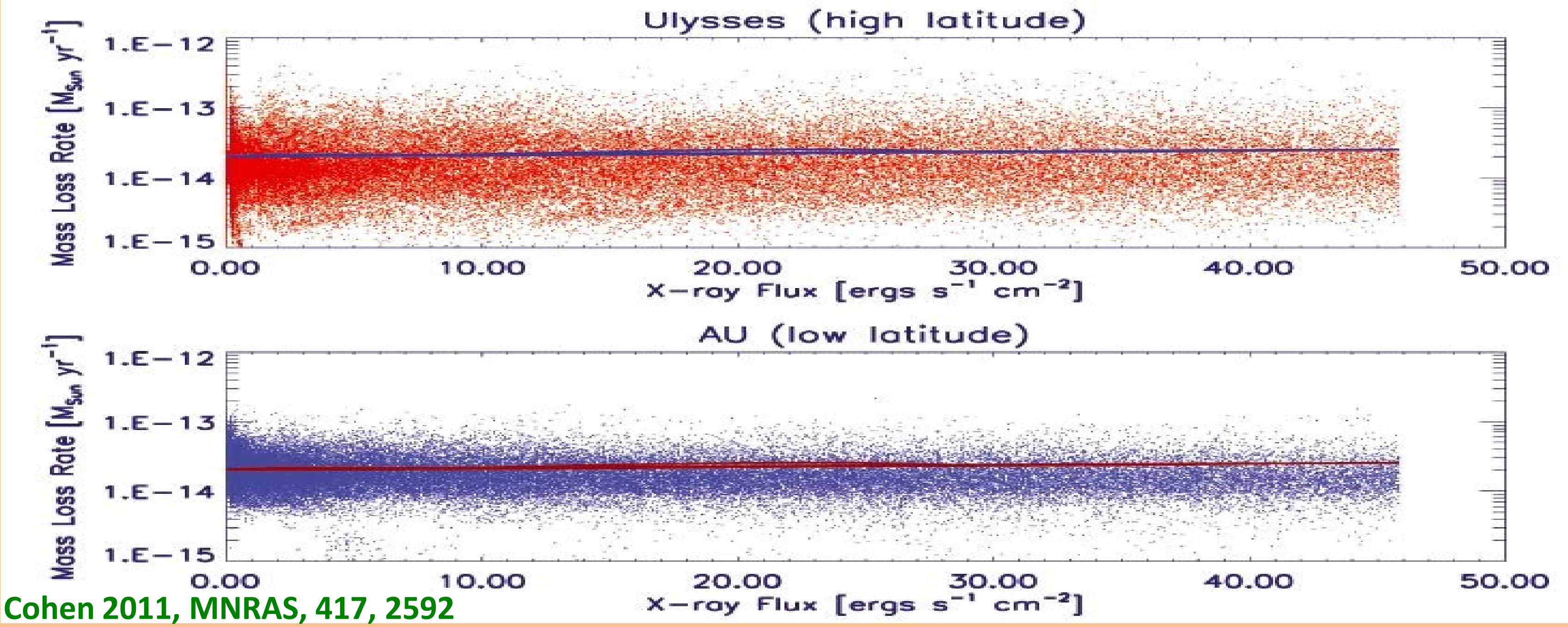
The Case for a Relatively Weak Wind for the Young Sun

Solar activity varies significantly over the course of its activity cycle, but:

1. Voyager has observed little variation from the canonical solar mass loss rate of $\dot{M}_{\odot}=2\times10^{-14}\ M_{\odot}/yr$.
2. There is no strong correlation between solar X-ray flux and mass loss rate.

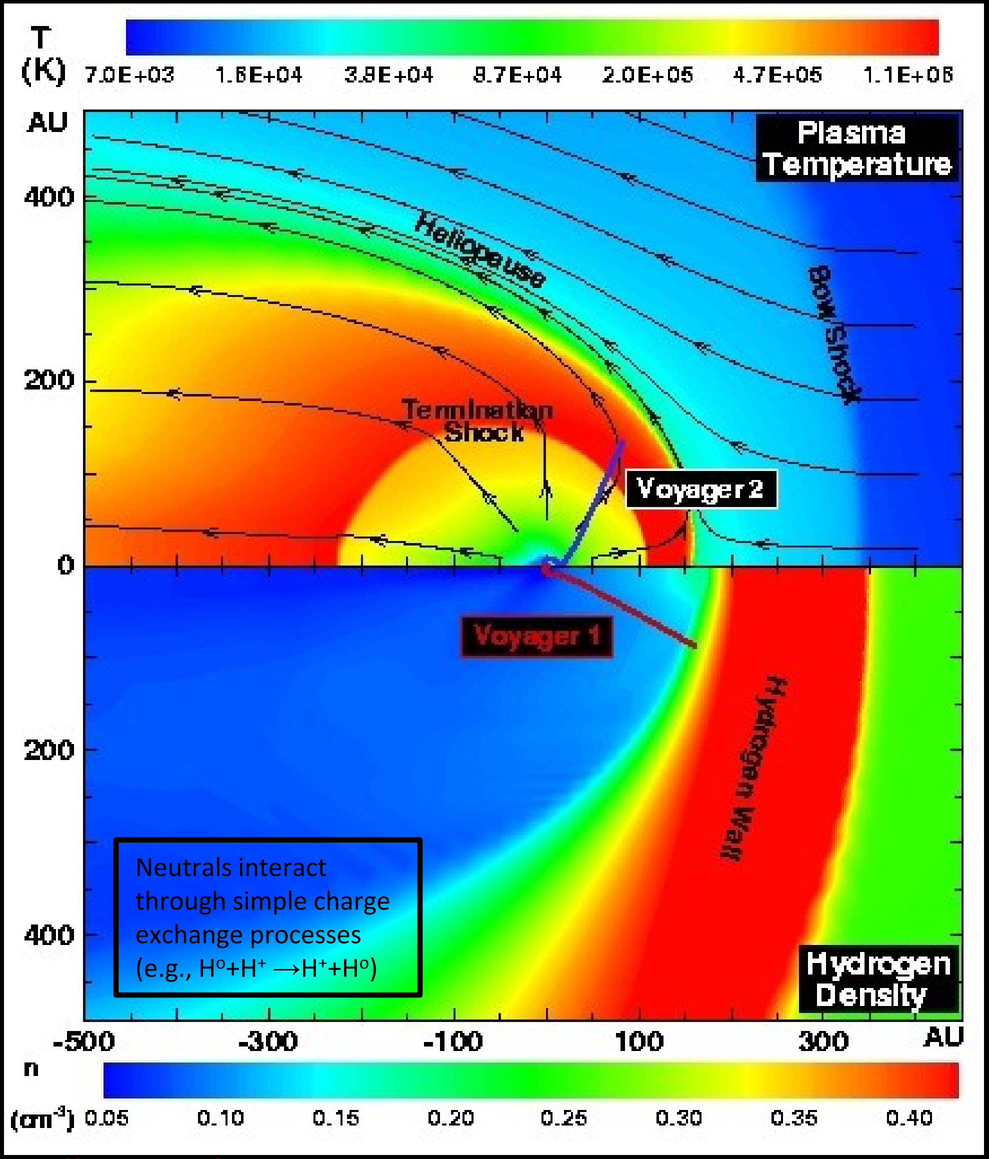
Conclusion: Perhaps the solar wind is relatively constant over time.





Cohen 2011, MNRAS, 417, 2592

The Global Heliosphere

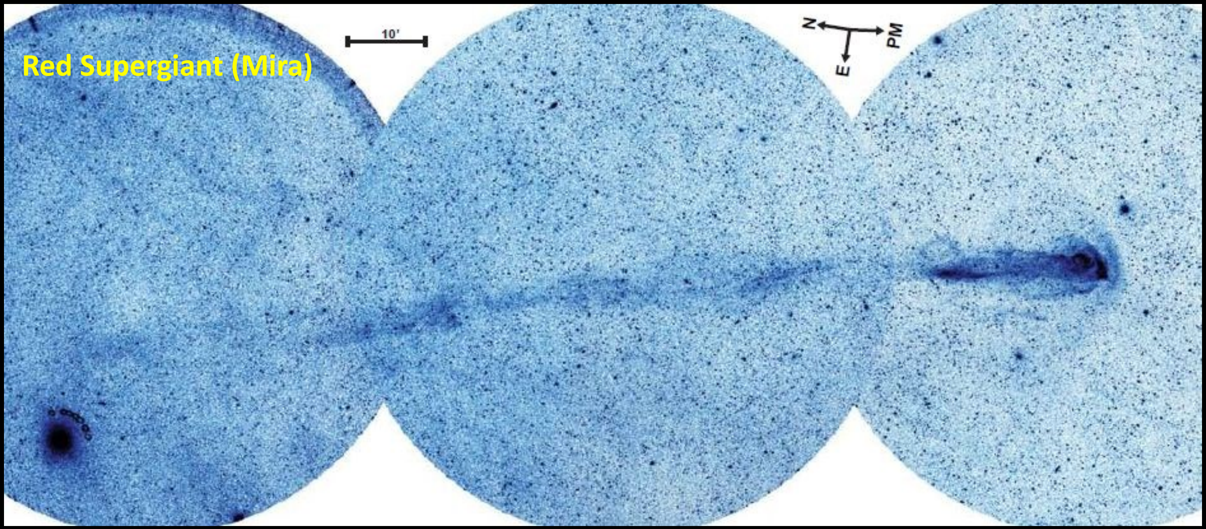


Müller & Zank 2004, JGR, 109, 7104

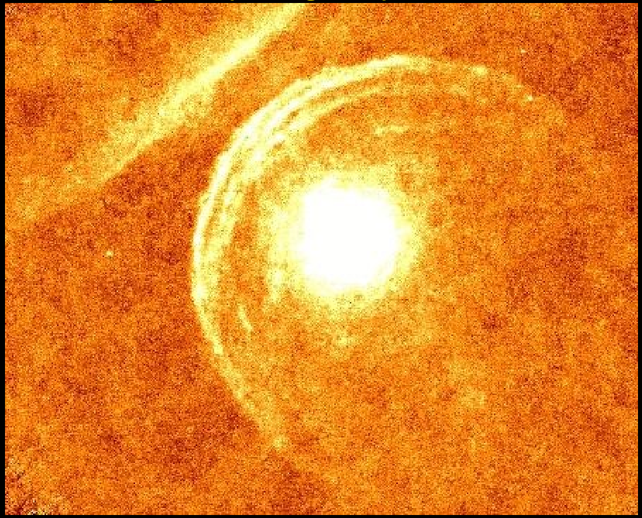
The only known method of detecting solar-like coronal winds around other stars is by detecting Lyman- absorption from stellar "astrospheres," analogous to our own global heliosphere.

Astrosphere Images

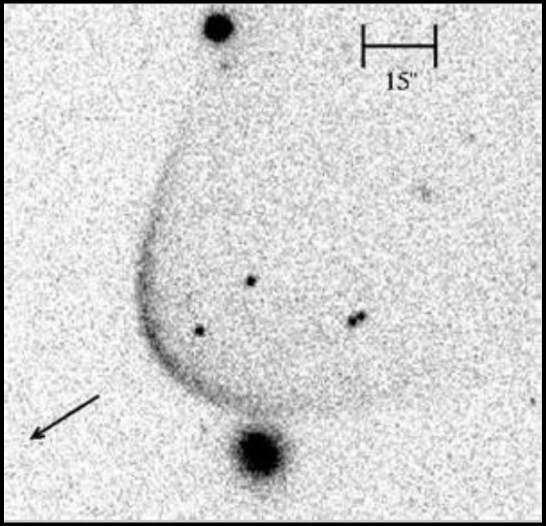

Young Star (LL Ori)



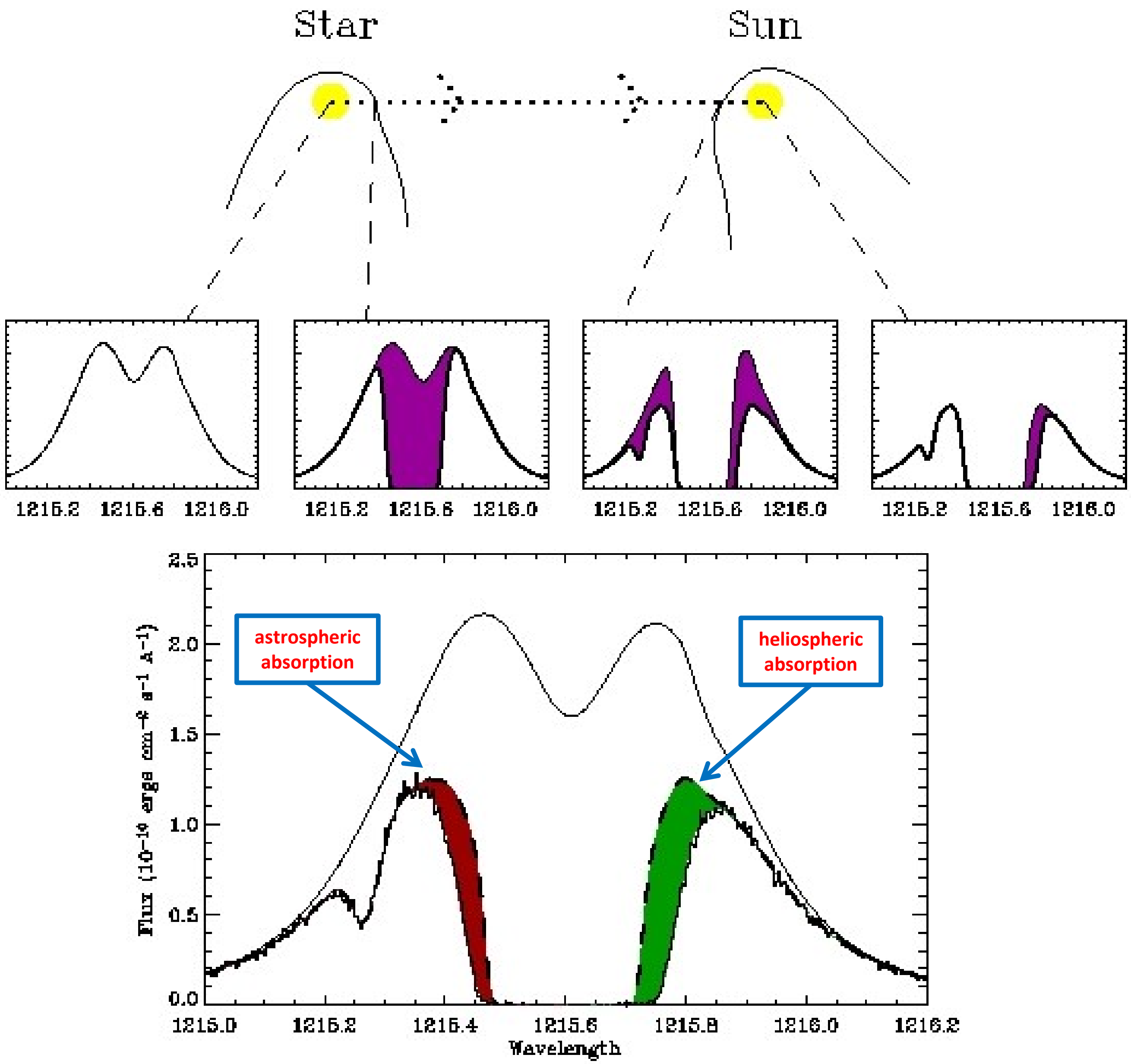
Red Supergiant (Mira)

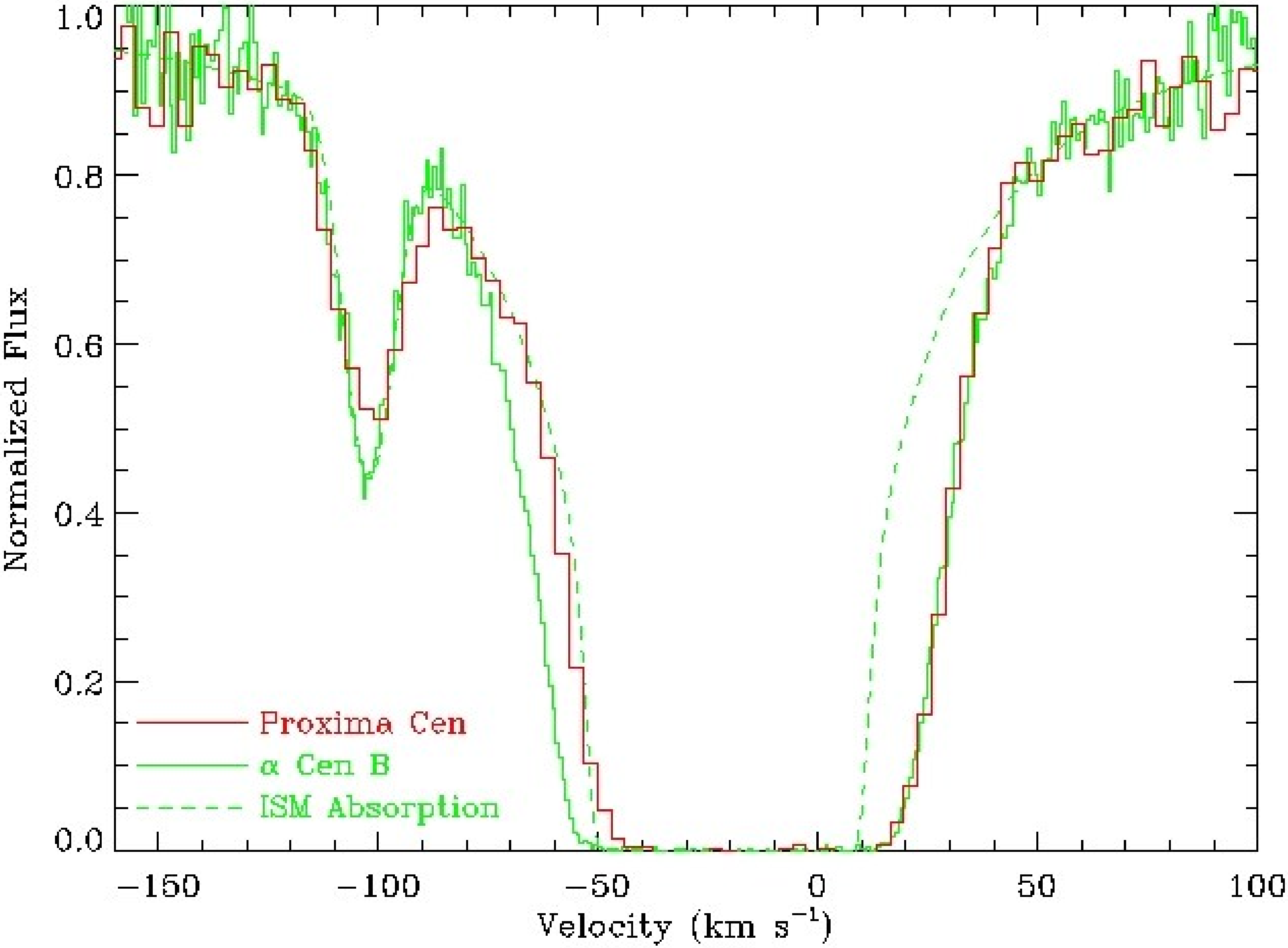
Red Supergiant (Betelgeuse)



Massive Hot Star

Pulsar


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


Star
Sun
1215.2 1215.6 1216.0
1215.2 1215.6 1216.0
1215.2 1215.6 1216.0
1215.2 1215.6 1216.0
astrospheric absorption
heliospheric absorption
Flux (10^{-13} ergs cm^{-2} s^{-1} Å^{-1})
2.5
2.0
1.5
1.0
0.5
0.0
1215.0
1215.2
1215.4
1215.6
1215.8
1216.0
1216.2
Wavelength



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

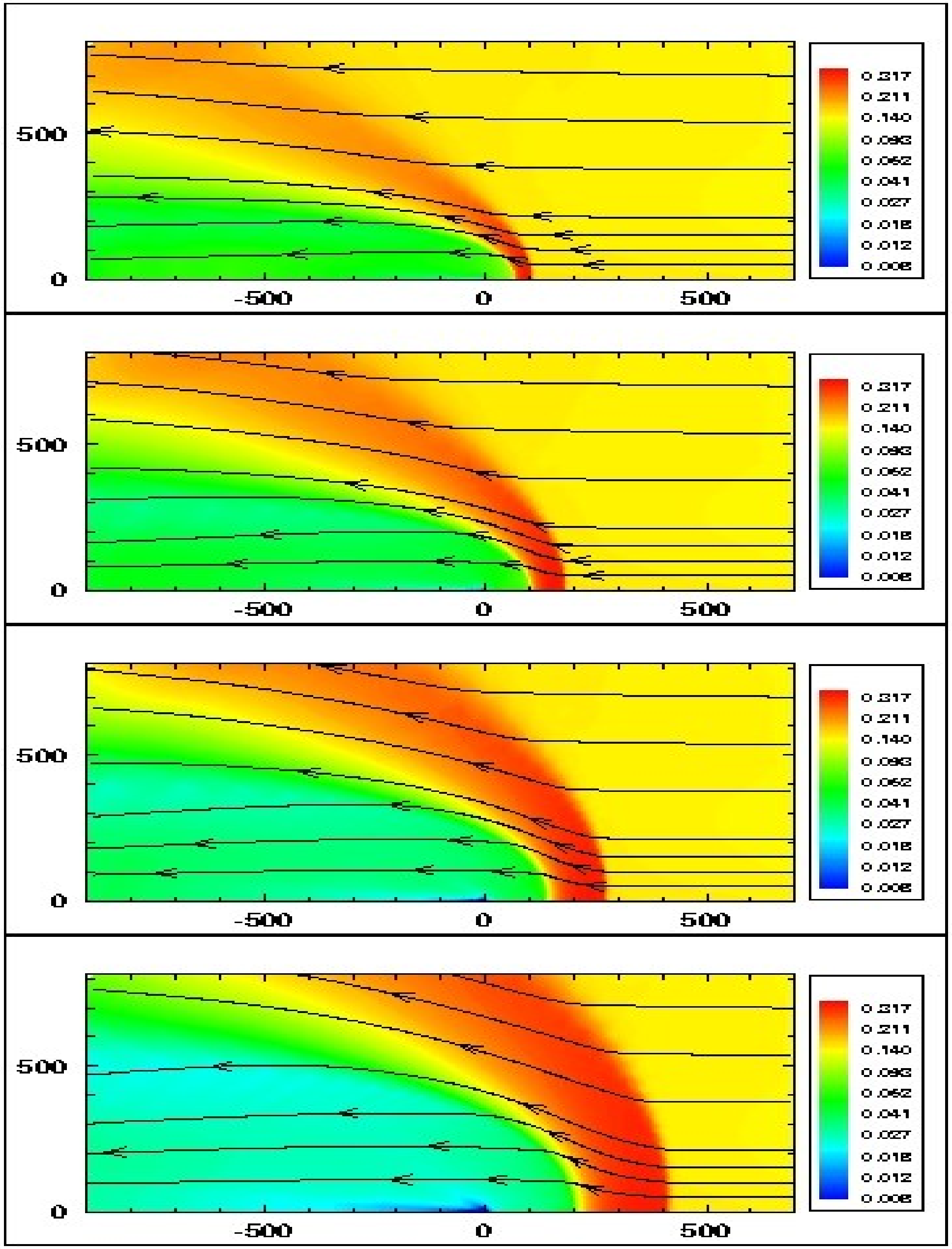
Models of the α Cen Astrosphere

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

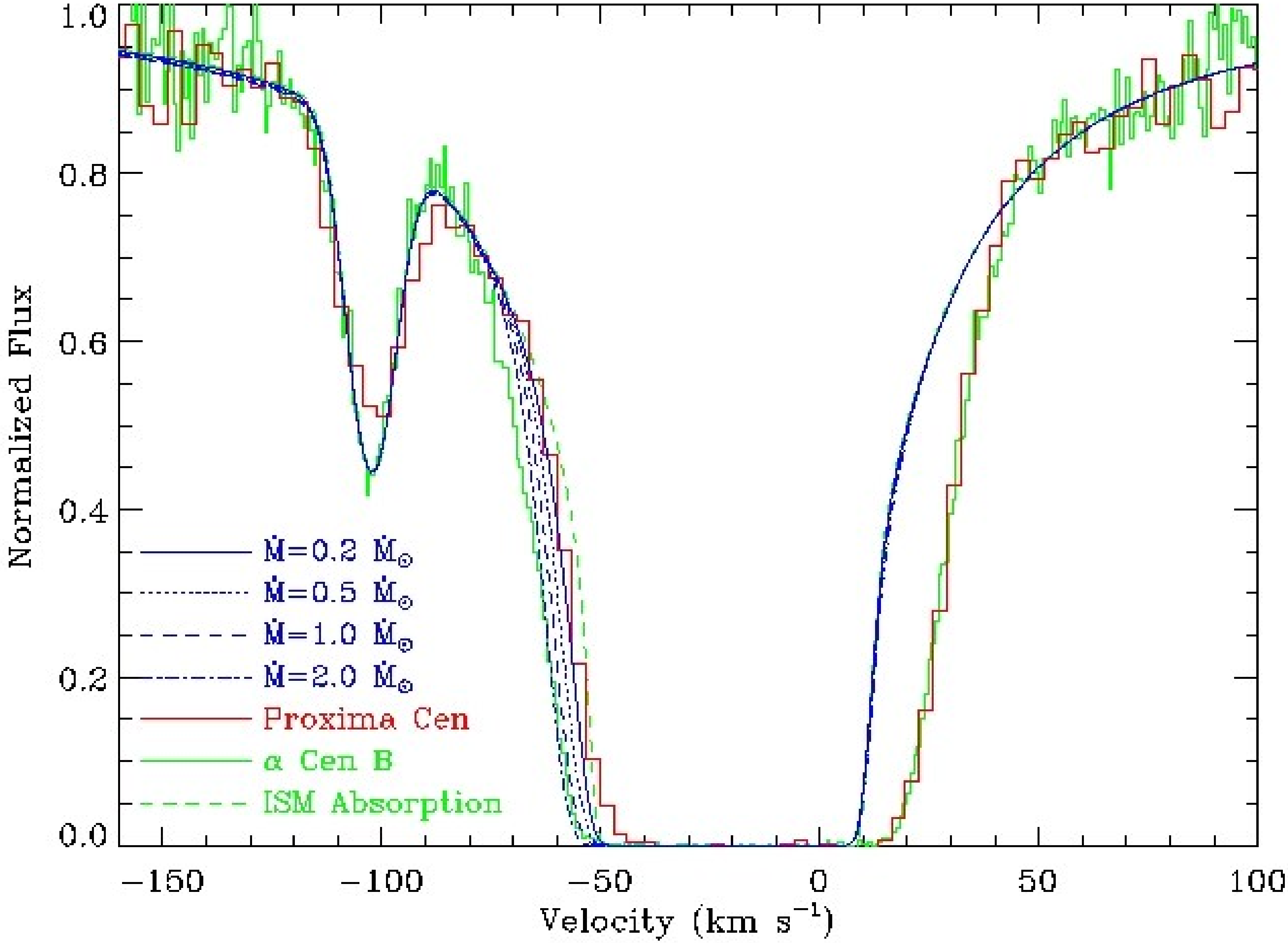
$\dot{M}=0.5\ \dot{M}_\odot$

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

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

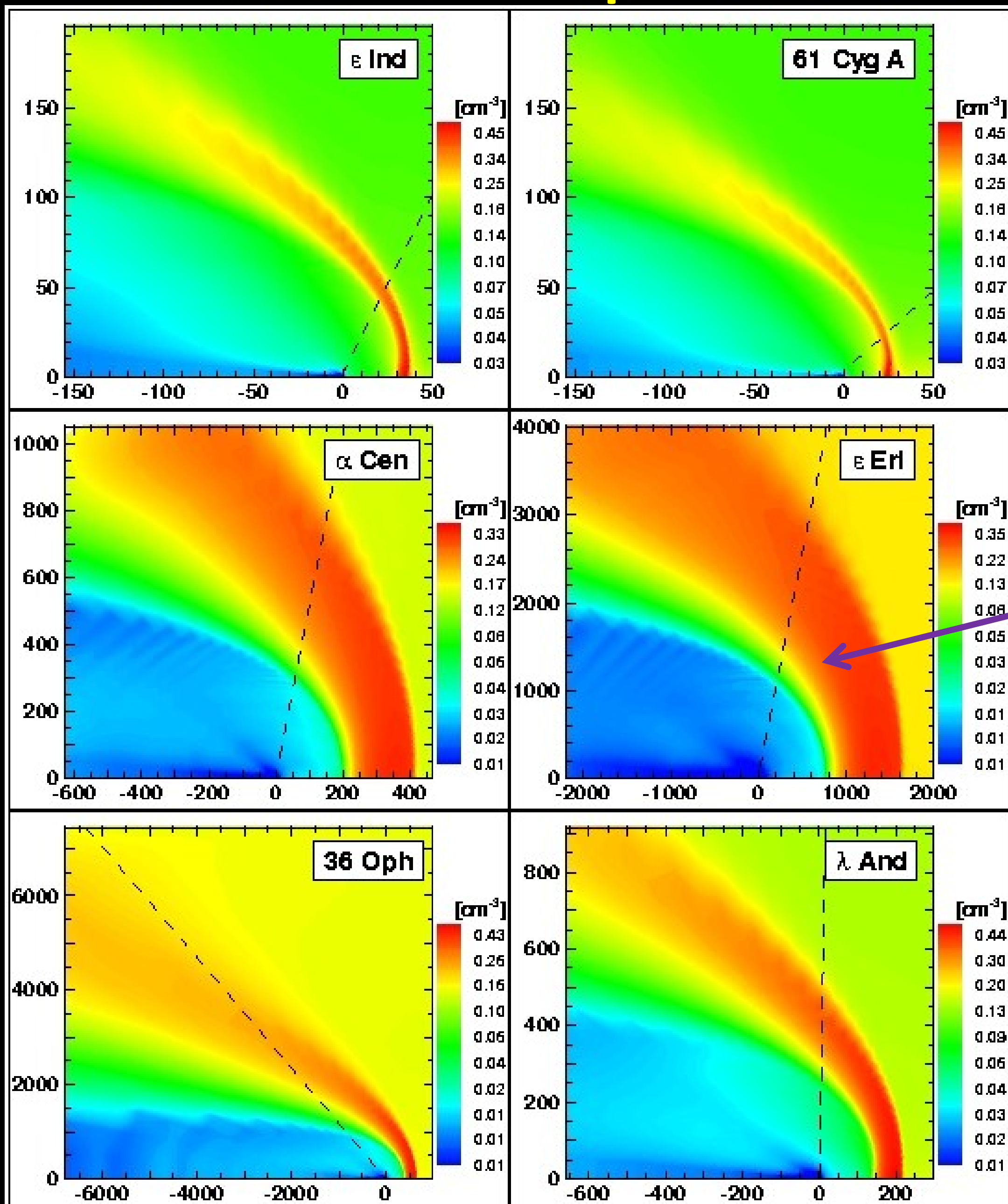


Astrospheric Absorption Predictions for α Cen



Wood et al. 2001, ApJ, 547, L49

Astrospheric Models



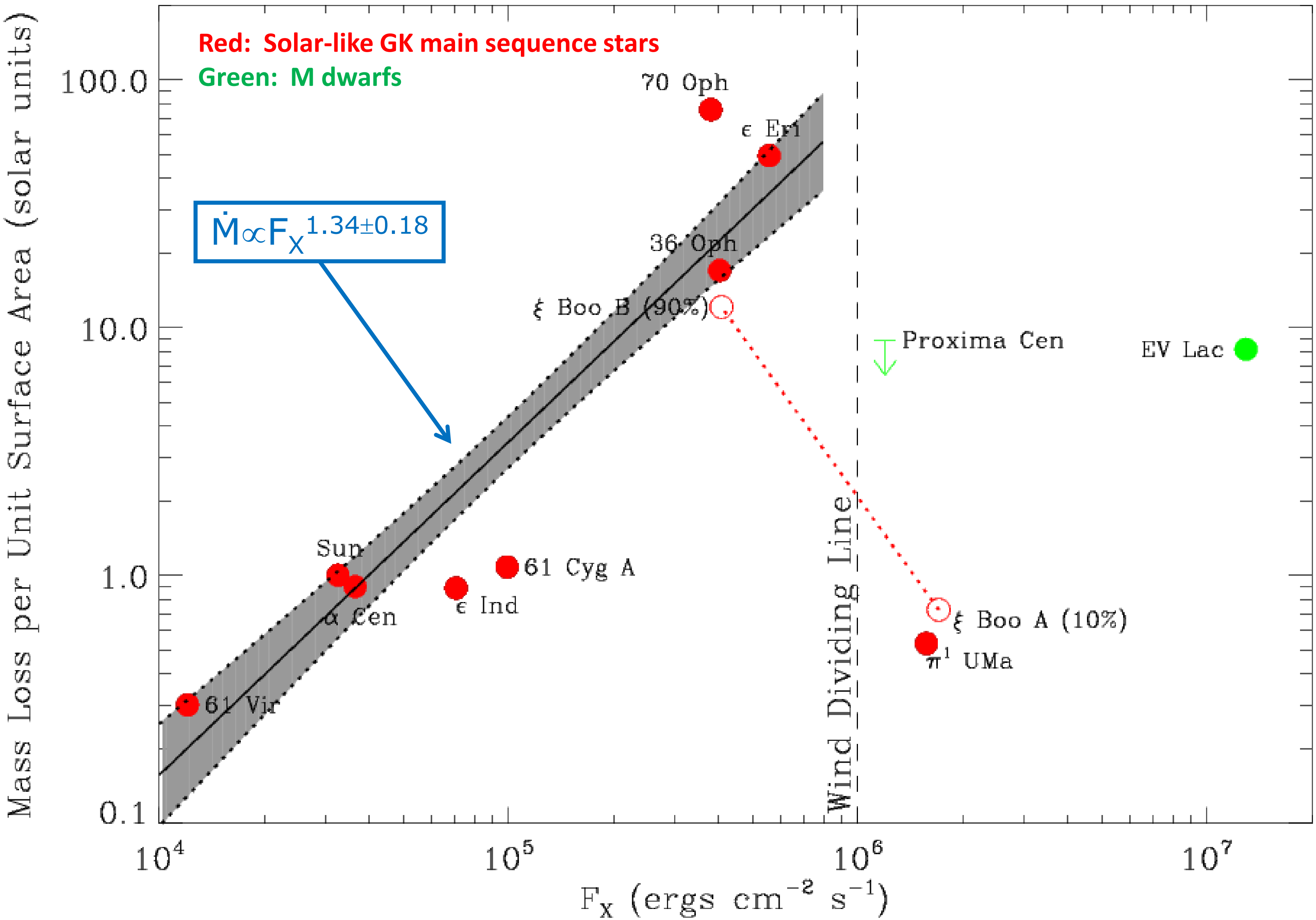
The ε Eri astrosphere is comparable in size to the full moon in the night sky!

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



Wood et al. 2014, ApJ, 781, L33

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

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

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

$$F_x \propto V_{rot}^{2.9 \pm 0.3} \text{ (Ayres 1997)}$$

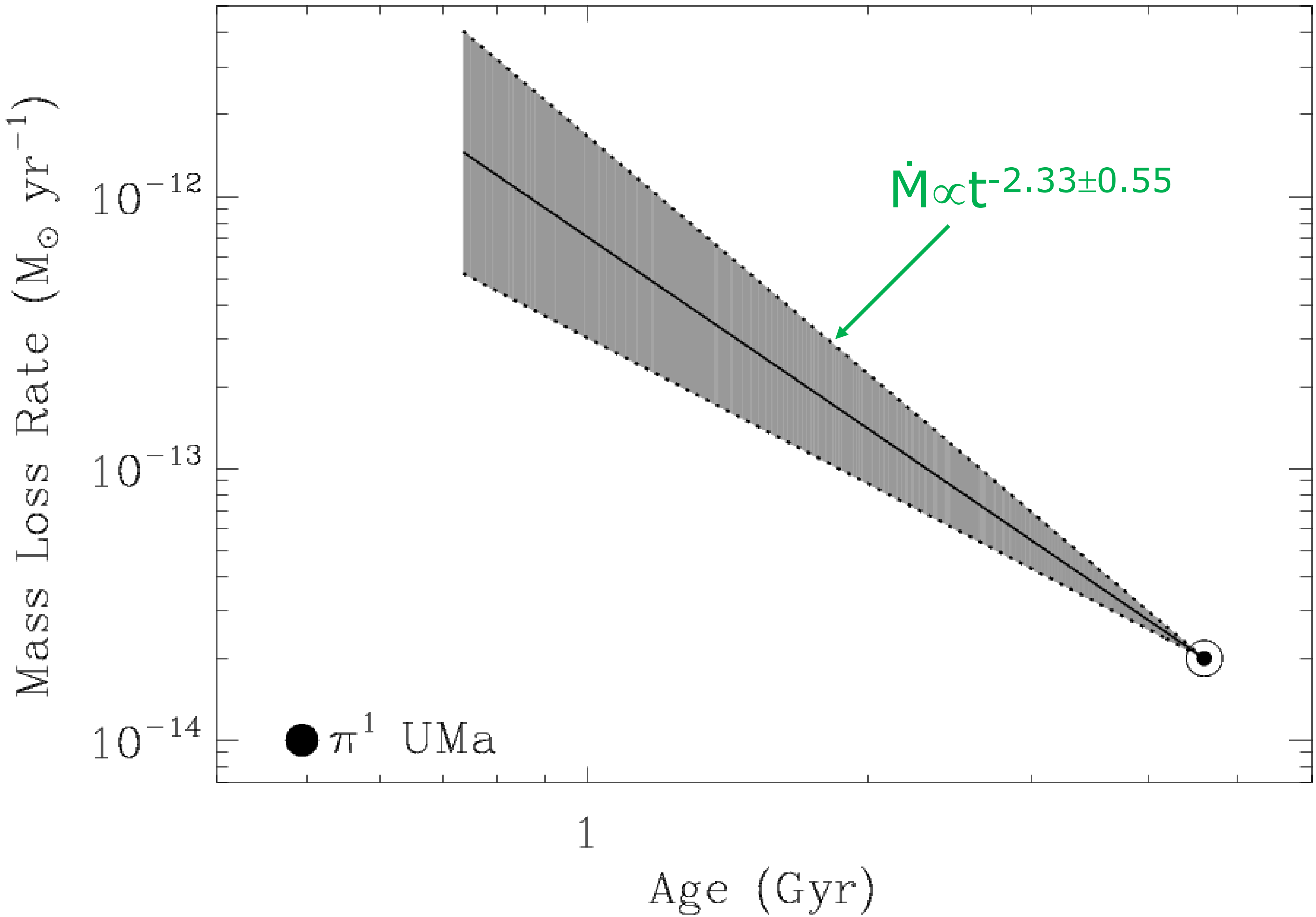
Rotation rate (V_{rot}) vs. age (t):

$$V_{rot} \propto t^{-0.6 \pm 0.1} \text{ (Ayres 1997)}$$

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

$$\dot{M} \propto t^{-2.33 \pm 0.55}$$

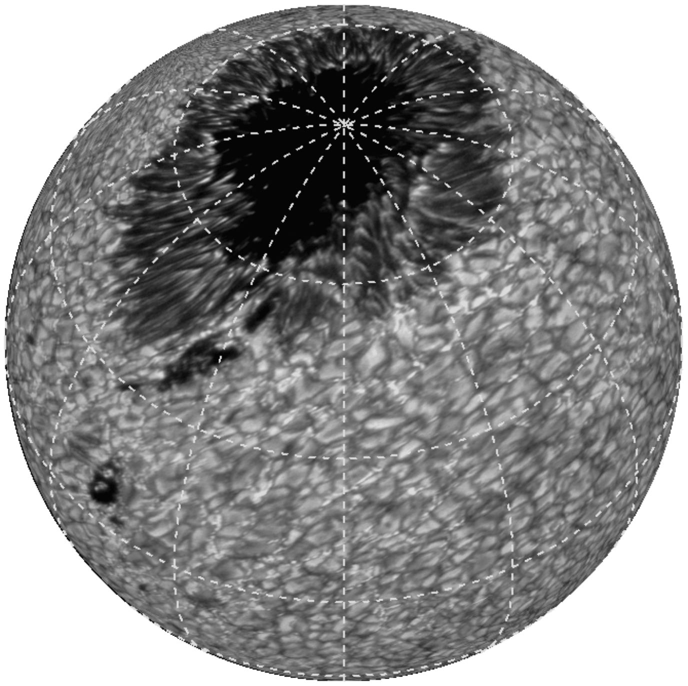
Wind Evolution for a Sun-like Star



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

Polar Spots?

(e.g., Strassmeier 2002, AN, 323, 309)



Toroidal Fields?

(e.g., Vidotto et al. 2016, MNRAS, 455, L52)

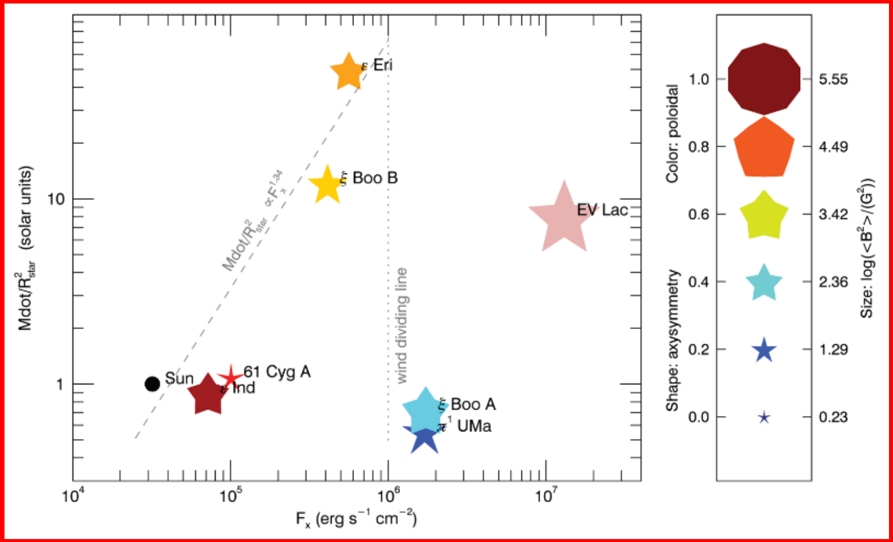


Table 2. Magnetic properties of our sample. EV Lac, ξ Boo A and ϵ Eri had their properties averaged over multi-epochs (Appendix A).

Star ID	$\langle B^2 \rangle$ (G^2)	$\langle B^2_{pol} \rangle$ (G^2)	$\langle B^2_{tor} \rangle$ (G^2)	$\langle B^2_{axi} \rangle$ (G^2)	$\langle B^2_{dip} \rangle$ (G^2)	f_{pol}	f_{tor}	f_{axi}	f_{dip}	Reference for surface magnetic map
EV Lac	3.6×10^5	3.4×10^5	1.7×10^4	1.0×10^5	2.5×10^5	0.95	0.05	0.31	0.72	Morin et al. (2008)
ξ Boo A	1.8×10^3	6.6×10^2	1.1×10^3	3.4×10^2	1.2×10^3	0.37	0.63	0.51	0.43	Morgenthaler et al. (2012)
π^1 UMa	1.1×10^3	2.0×10^2	8.9×10^2	3.3×10^1	7.4×10^2	0.18	0.82	0.16	0.68	Petit et al. (in preparation)
ϵ Eri	2.7×10^2	2.0×10^2	7.5×10^1	7.8×10^1	2.0×10^2	0.72	0.28	0.40	0.75	Jeffers et al. (2014)
ξ Boo B	4.0×10^2	2.7×10^2	1.3×10^2	7.3×10^1	1.8×10^2	0.68	0.32	0.27	0.45	Petit et al. (in preparation)
61 Cyg A	4.5×10^1	3.9×10^1	5.7×10^0	8.2×10^{-1}	8.6×10^0	0.87	0.13	0.02	0.19	Boro Saikia et al. (in preparation)
ϵ Ind	5.8×10^2	5.6×10^2	2.0×10^1	2.8×10^2	3.3×10^2	0.96	0.04	0.51	0.56	Boisse et al. (in preparation)

Why Don’t Massive Flare Rates Seem to Yield Massive CME-Driven Winds?

The Astrophysical Journal Letters, 804:L28 (6pp), 2015 May 10
doi:10.1088/2041-8205/804/2/L28

WHY IS THE GREAT SOLAR ACTIVE REGION 12192 FLARE-RICH BUT CME-POOR?

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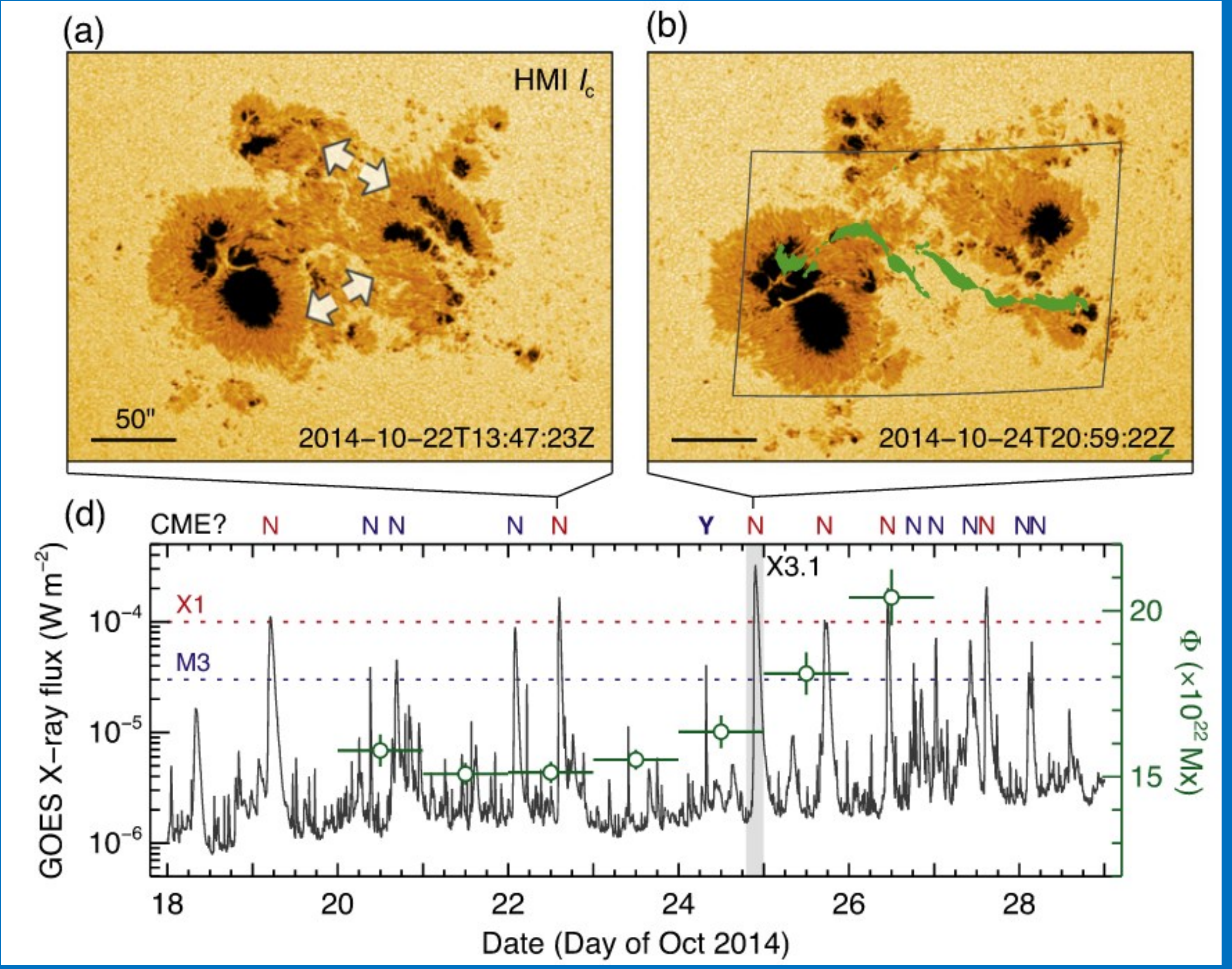
Received 2015 January 17; accepted 2015 April 17; published 2015 May 5



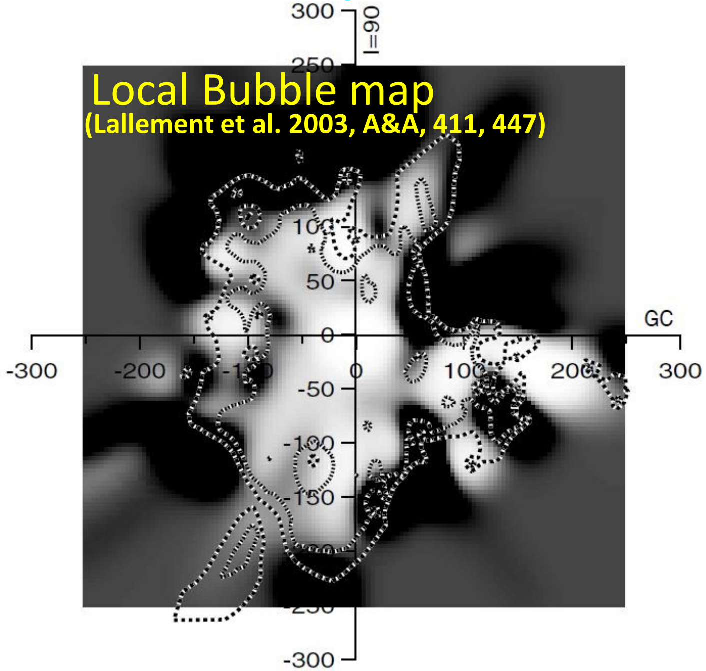
1. Perhaps active star active regions are like the recent solar AR 12192, which produced many flares but not CMEs.
2. What is it about this solar AR that inhibited CMEs?
   - Is it the strength of confining overlying fields?
   - Or is it some more subtle characteristic of internal field topology?

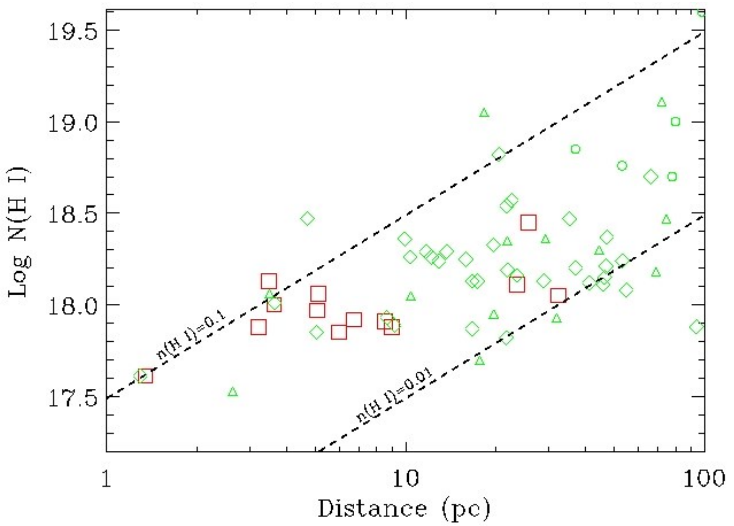
Obstacles to Wind Detection via Astrospheres

(Why so few astrosphere detections since 2005?)

I. The astrospheric detection likelihood per observation is generally very low, as the Sun lies within the Local Bubble (LB), within which most of the ISM is fully ionized.
   A. By chance, the Sun lies within a small, partially neutral cloud (LIC=Local Interstellar Cloud) within the LB, so it and many very nearby stars are surrounded by neutrals and have detectable astrospheres.
   B. But beyond 10 pc, the astrosphere detection fraction plunges dramatically, due to most of the ISM being ionized.

II. Instrumental difficulties
   A. Detection requires high-res UV spectroscopy (e.g. HST/STIS or HST/GHRS). Once HST is gone, that will be it for this wind detection method for the foreseeable future.
   B. HST/STIS unavailable from 2004-2009.
   C. HST/COS installed in 2009. This means much less use of STIS/E140M, and fewer usable Lyman-α spectra being added to the HST archives.

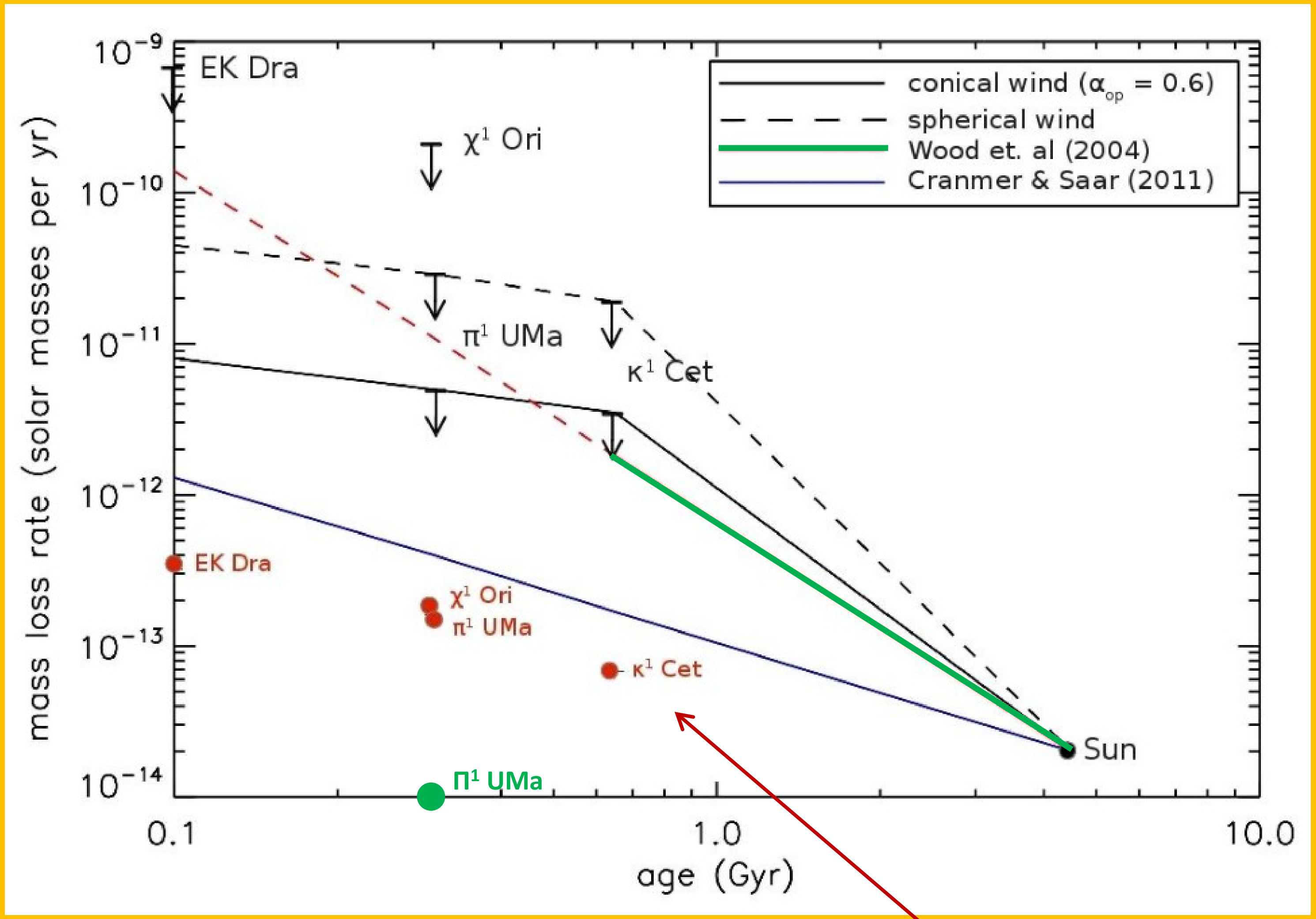




Wood et al. 2005, ApJS, 159, 118

Is Radio the Future of Stellar Wind Detection?

Below are recent VLA/ALMA constraints from Fichtinger et al. (2017, A&A, 599, A127)



Predictions from angular momentum evolution studies

Indirect methods: Debris disks (AU Mic; Schüppler et al. 2015, A&A, 581, 97)
Exoplanets (see other talks this conference!)

SUMMARY

- Currently the only way to detect the 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.
- 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.