Stellar Winds and mass loss rates of young solar-like stars

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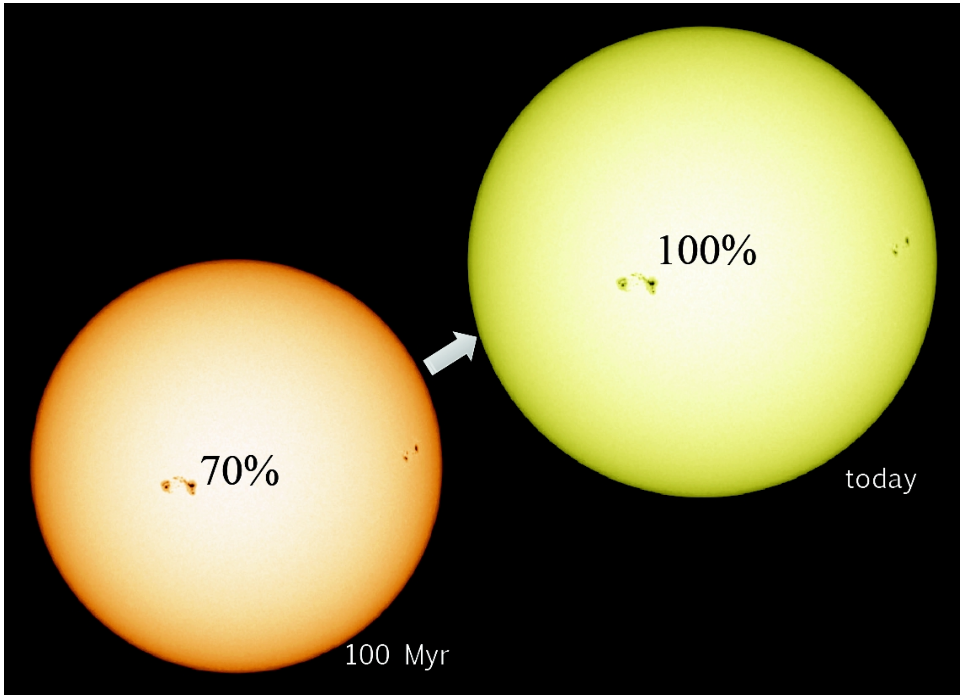
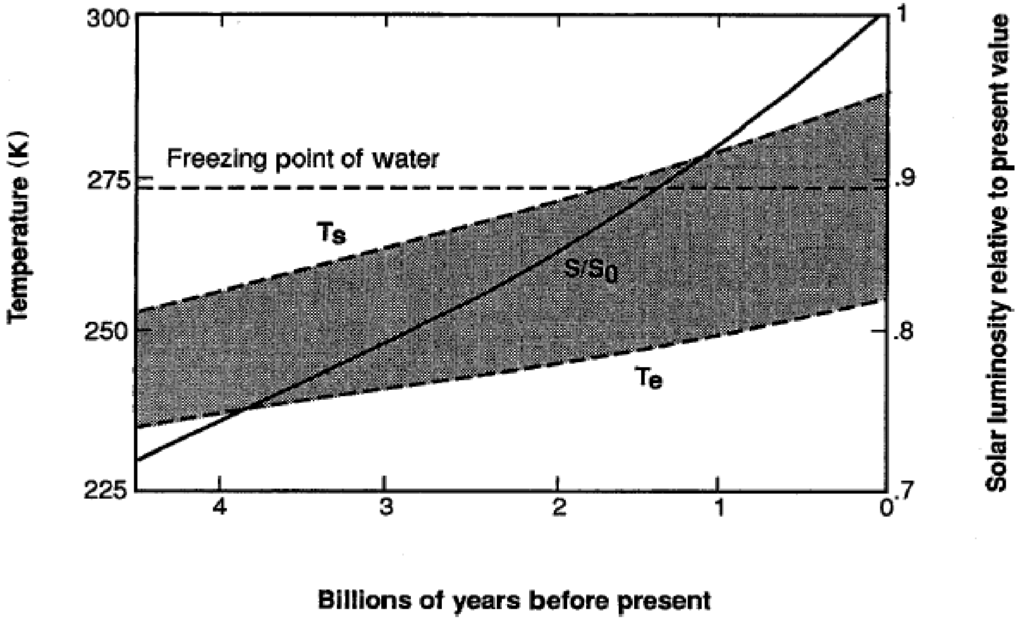
The Faint Young Sun



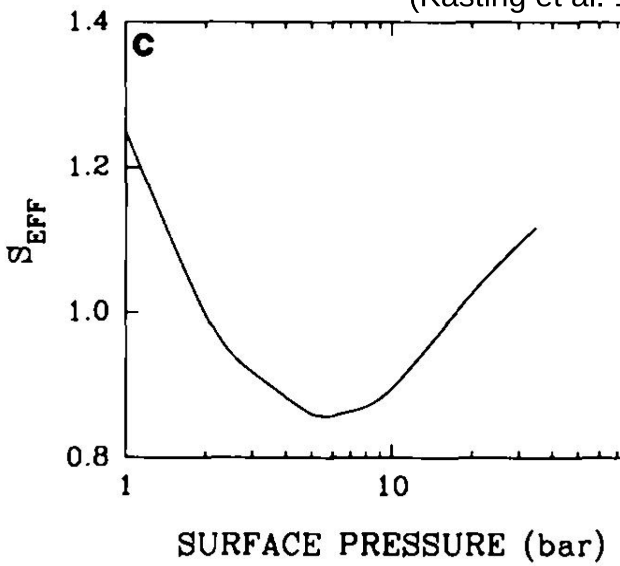


Kasting & Catling (2003)

- 30% less luminous
- completely frozen surfaces of Earth and Mars
- problem with habitability of young Earth and Mars

Greenhouse Effect

(Kasting et al. 1991)



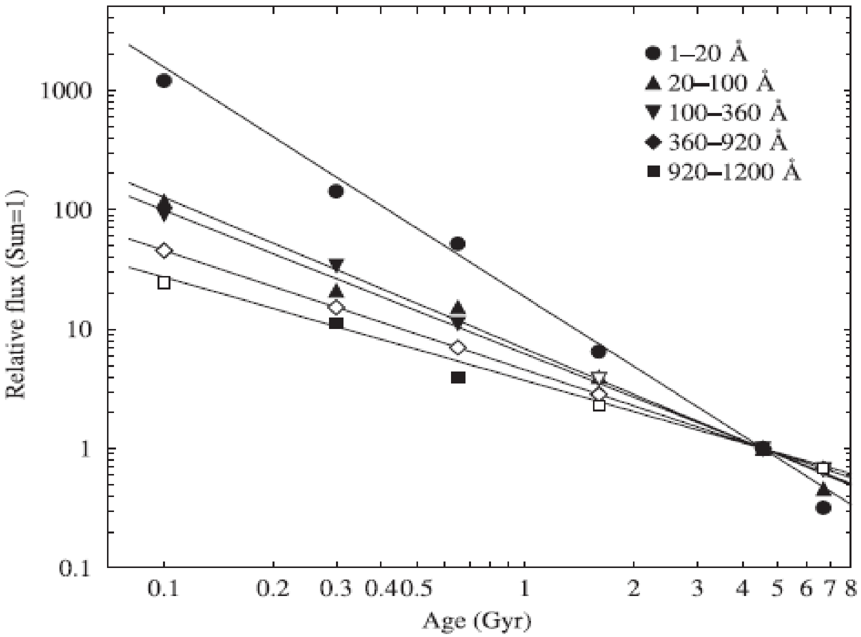
- but Mars had liquid water on surface, therfore was warm enough
- CO2 atmosphere and greenhouse: any CO2 pressure insufficient to produce T > 273 K in young Mars

- too much: evaporation of terrestrial oceans
- too little: no liquid water on Mars
- just right: **1.03 M < MZAMS < 1.07 M**

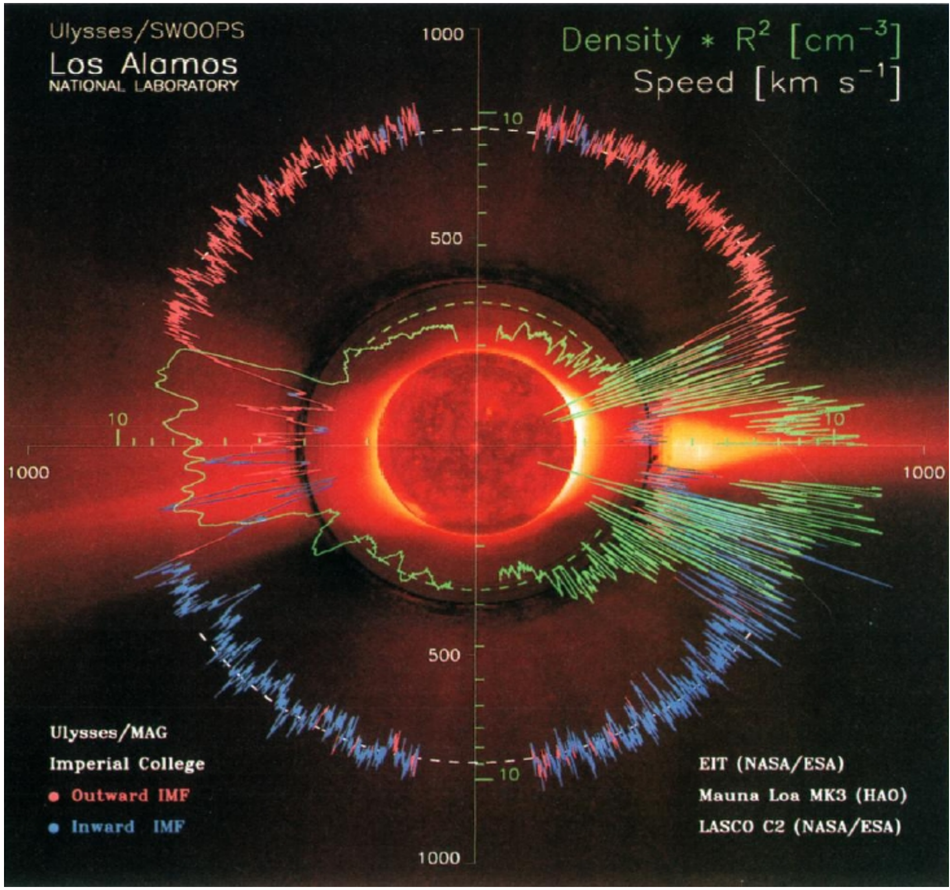
(Kasting 1988, 1991; Kasting et al. 1993; Sackmann & Boothroyd 2003)

Solutions to the FYSP

- geological evidence for warmer climate
- solution to FYSP: a **higher solar luminosity**, a **lower overall albedo** or significantly **enhanced greenhouse effect**
- higher luminosity: higher initial stellar mass → stronger wind for young solar-like stars



Wood et al. (2005)



Observations of stellar winds

- JVLA: 27 antennas of 25 m diameter positioned along three equiangular arms of length 21 km
- maximum resolution of 1.4 arcsec at 1.4 GHz and 40 milliarcs at 50 GHz
- four standard configurations of maximum baseline lengths of 1, 3.4, 11, and 36 km, providing wide range of resolutions and image surface brightness sensitivities
- complete frequency coverage from 1 to 50 GHz

EVLA Band Characteristics

Band (GHz)	Letter Code	Available Bandwidth[b] (GHz)	Antenna SEFD[c] (Jy)	Sensitivity[a] Continuum (μJy beam^{-1})	Line (mJy beam^{-1})
1–2	L	0.7	400	5.5	2.2
2–4	S	1.75	350	3.9	1.7
4–8	C	3.5	300	2.4	1.0
8–12	X	3.8	250	1.8	0.65
12–18	Ku	5.5	280	1.7	0.61
18–26.5	K	8	450	2.3	0.77
26.5–40	Ka	8	620	3.2	0.90
40–50	Q	8	1100	5.6	1.4

Observations of stellar winds

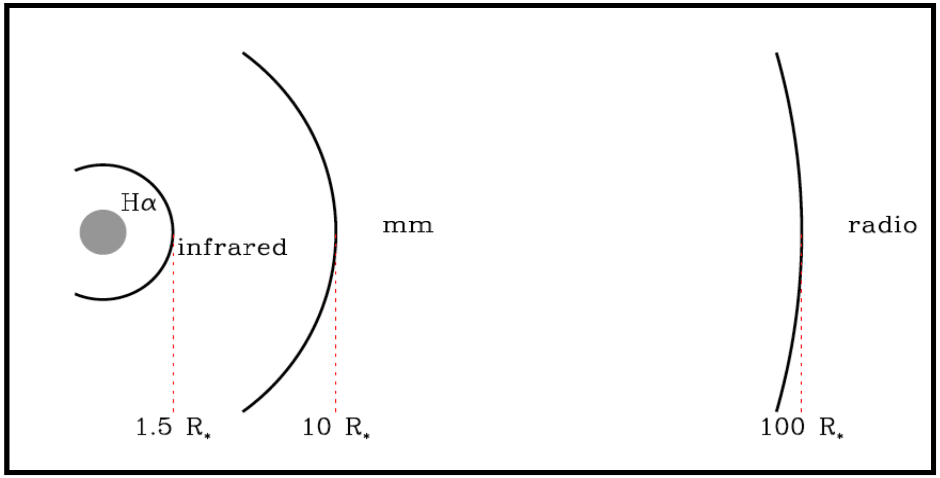
- direct observations: free-free radio emission of young solar analogs
- measuring radio bremsstrahlungs flux of an ionized wind
- if wind mass loss rate can be measured, the young Sun's total mass can be found by integration back in time

Name	HD	Spectral Type	d (pc)	T_{eff} (K)	Mass ($M_\odot$)	Radius ($R_\odot$)	log L_x (erg/s)	P_{rot} (days)	Age (Gyr)
χ^1 Ori	39587	G1 V	8.7	5890	1.01	0.96	28.99	5.24	0.3
EK Dra	129333	G1.5 V	34.0	5870	1.06	0.95	29.93	2.68	0.1
κ^1 Cet	20630	G5 V	9.2	5750	1.02	0.93	28.79	9.21	0.65
π^1 UMa	72905	G1.5 V	14.3	5850	1.03	0.95	29.10	4.90	0.3

Table 2. Target characteristics from the Sun in Time Program in Ribas et al. (2005) and Güdel (2007).

Radio free-free emission of ionized winds

- for hot stars:
- cool star wind:
- need to calculate radio emission and absorption for spherical wind



(Blomme 2011)

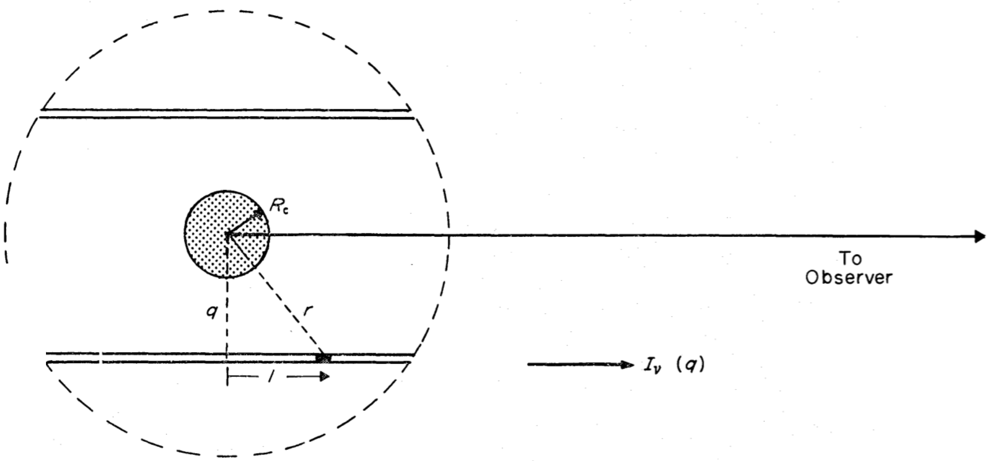
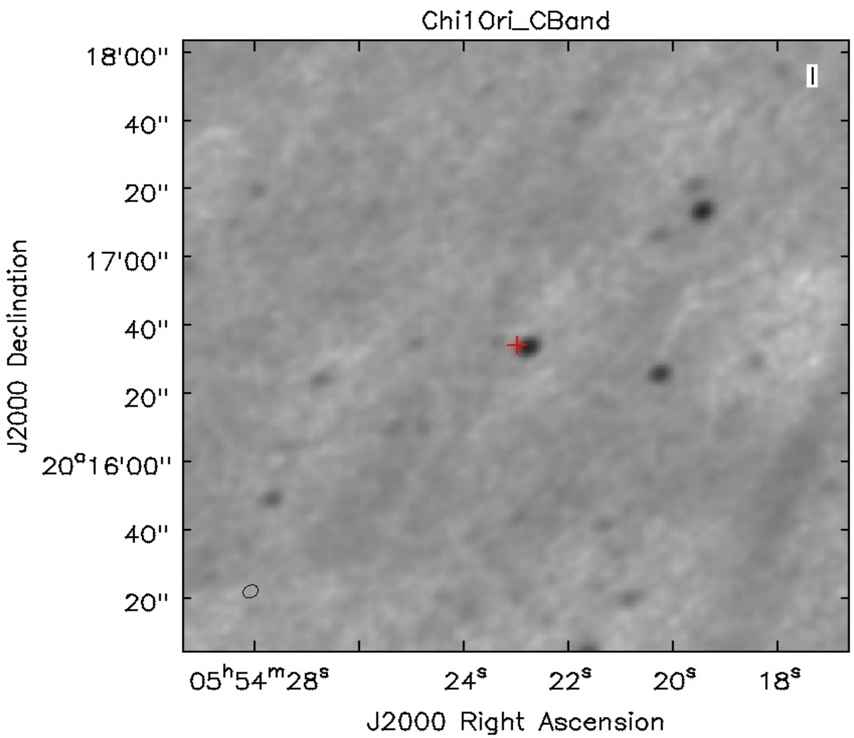


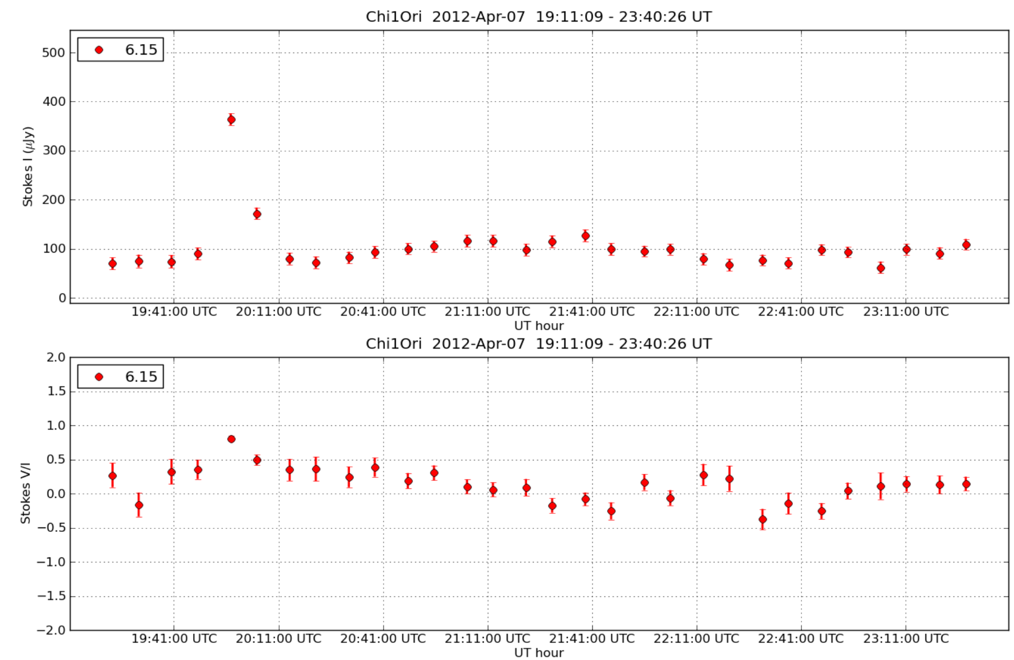
FIG. 1. *Geometry of the model.*

(Wright & Barlow 1975)

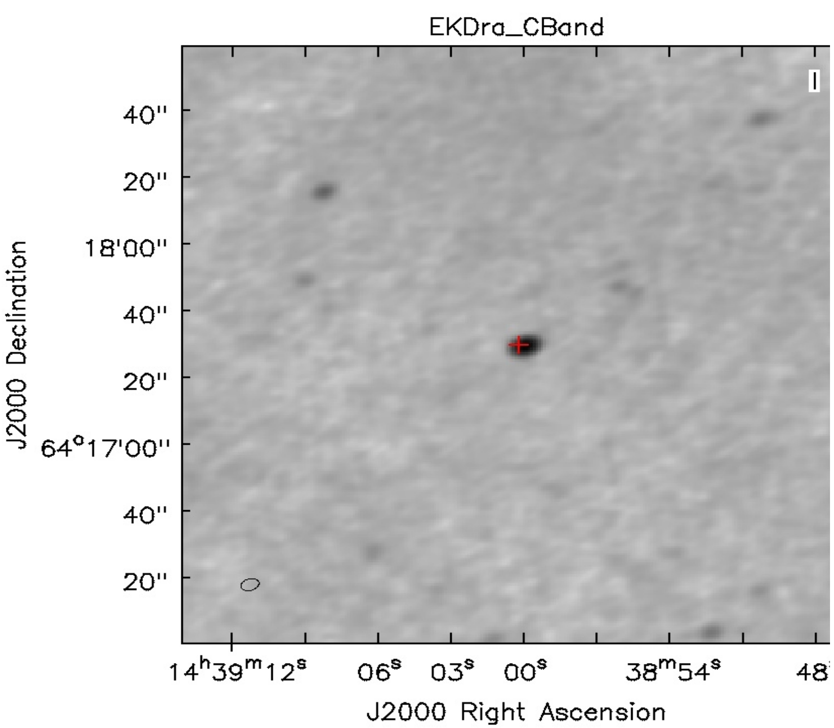
$$S_\nu = 8.3 \times 10^{-4}\ \mathrm{mJy} \left(\frac{\dot{M}}{10^{-10} M_\odot/\mathrm{yr}}\right)^{4/3} \left(\frac{v}{400\ \mathrm{km/s}}\right)^{-4/3} \left(\frac{T}{10^6\ \mathrm{K}}\right)^{0.1} \left(\frac{d}{10\ \mathrm{pc}}\right)^{-2} \nu_{\mathrm{GHz}}^{0.6}$$

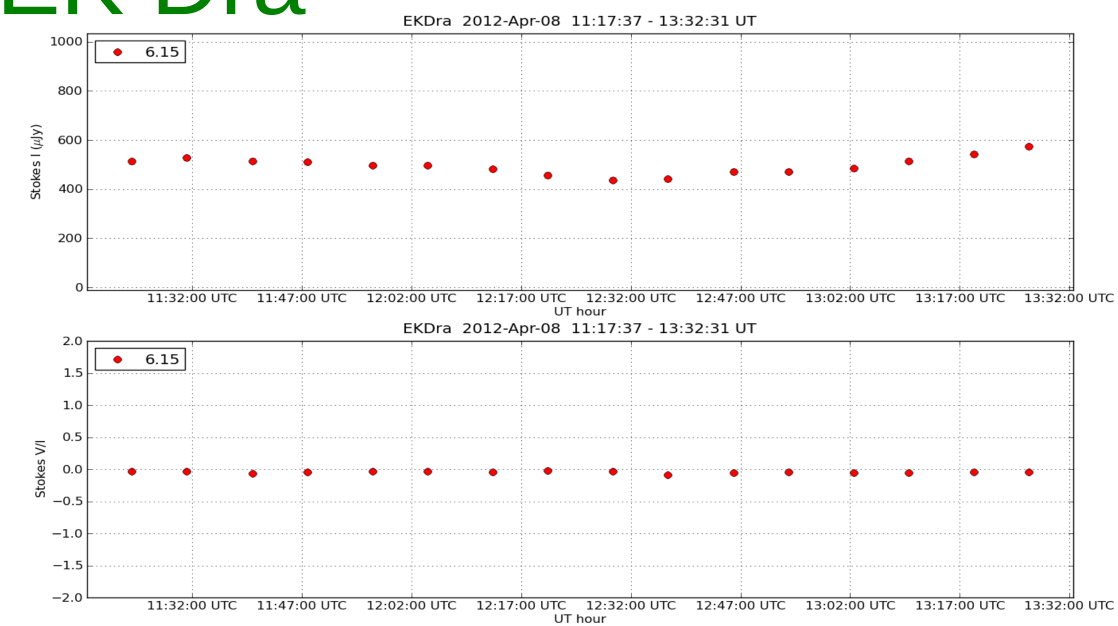
chi¹ Ori

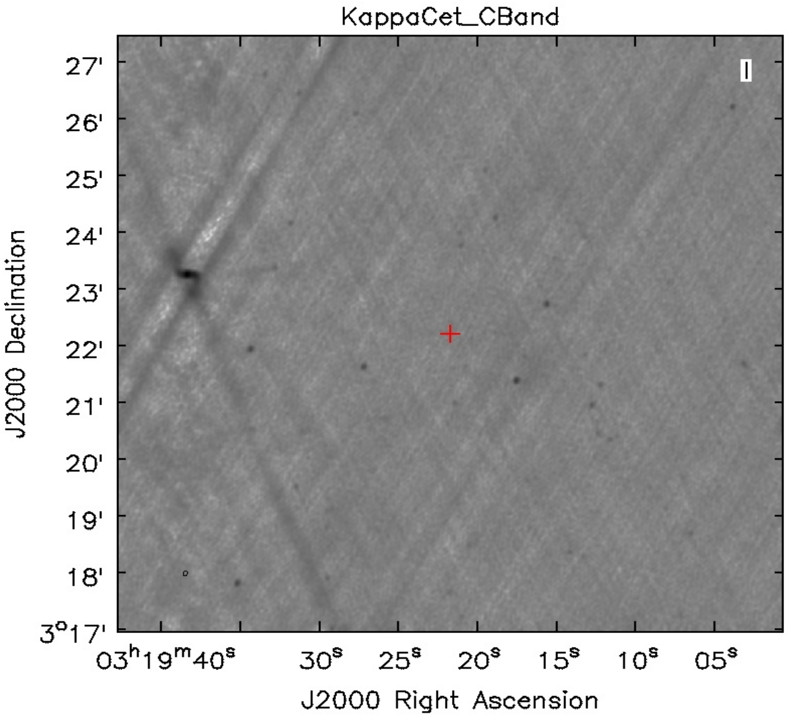




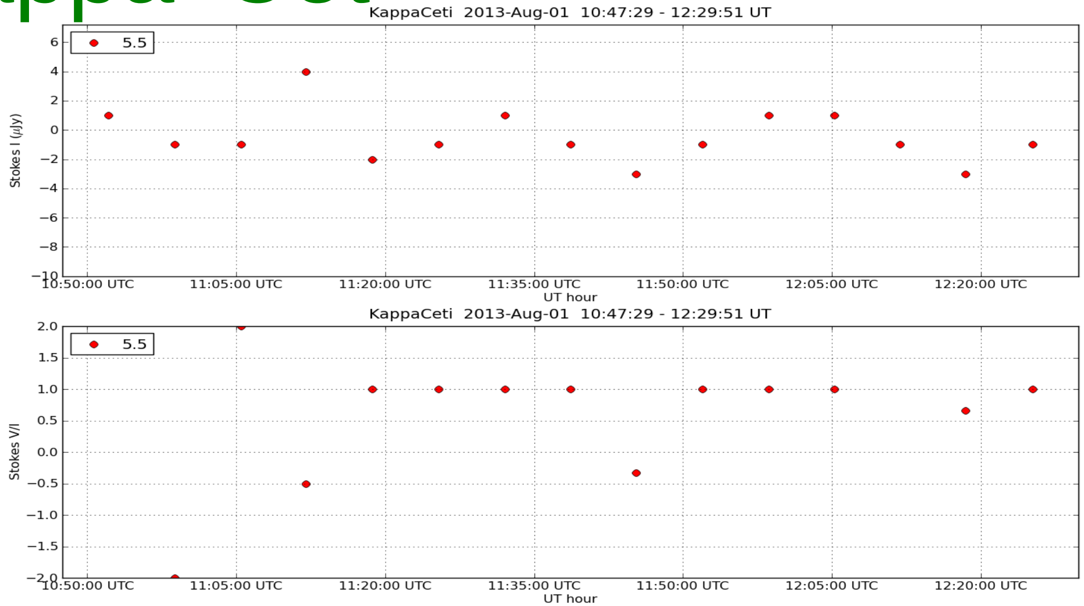
EK Dra

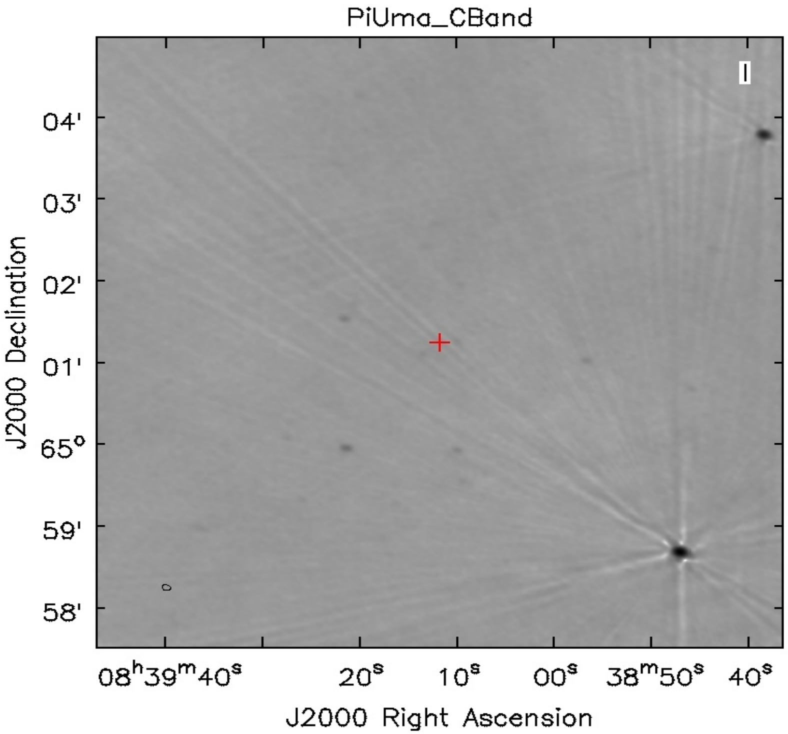




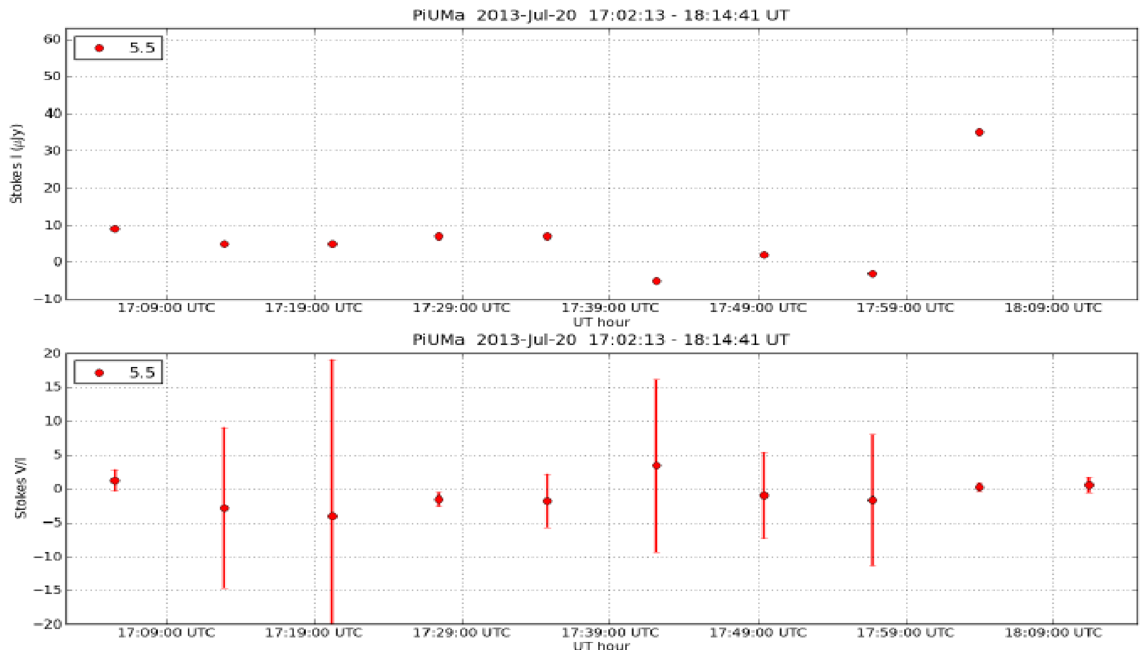


kappa[1] Cet





pi[1] UMa



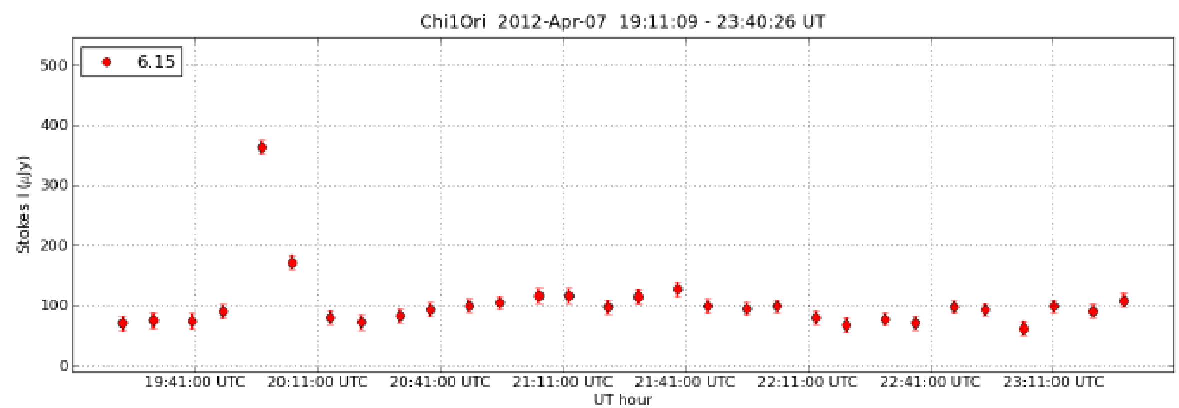
Radio fluxes

Thermal emission:

- positive slope in the spectrum (usually α = 0.6)
- no polarisation (Stokes V)
- no large time variation → hint of presence of flares!

Object	$S_\nu[\mu Jy]$ Stokes I		$S_\nu[\mu Jy]$ Stokes V	
	6 GHz	14 GHz	6 GHz	14 GHz
χ^1 Ori	110 ± 0.7	117 ± 2.7	14 ± 0.6	12 ± 1.1
EK Dra	593 ± 1.7	73 ± 2.4	-22 ± 0.8	-
κ^1 Cet	9	9	6.9	8.7
π^1 UMa	23.1	6.3	8.4	6.6

Table 3. The first two rows are the detected objects and their fluxes and uncertainties in Stokes I and Stokes V, respectively. The last two rows are the non-detections; their fluxes are determined by taking the 3 σ as estimation, where $\sigma = \sqrt{(rms)^2}$.



- chi[1] Ori & EK Dra (detections): active stars, flares, Stokes V component → radio emission is mostly non-thermal emission and hence no stellar wind!

Detection of Radio Flares

- detections: no mass loss rates for thermal wind
- non-thermal radio sources cannot be significantly larger than the stellar disk
- → radio source must be located close to stellar surface : $R_\nu = R_*$
- non-thermal emission must originate from above optically thick surface → upper limits for mass loss

$$\frac{R(\nu)}{R_\odot} \approx 6\left(\frac{\nu}{10\ \mathrm{GHz}}\right)^{-2/3}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-1/2}\left(\frac{\dot{M}}{10^{-10}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{2/3}\left(\frac{v_\infty}{300\ \mathrm{km\ s}^{-1}}\right)^{-2/3}$$

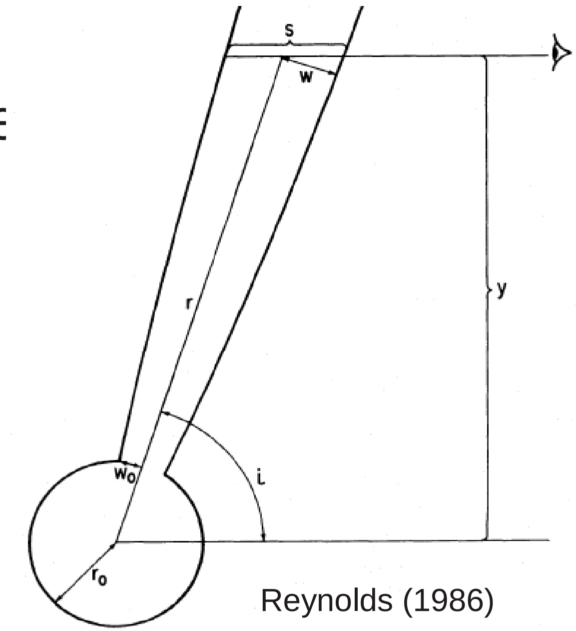
	10^4 K	10^5 K	10^6 K
EK Dra (C)	$1.3 \times 10^{-13}\ M_{sun}/yr$	$4.0 \times 10^{-12}\ M_{sun}/yr$	$1.3 \times 10^{-10}\ M_{sun}/yr$
EK Dra (Ku)	$6.9 \times 10^{-13}\ M_{sun}/yr$	$2.2 \times 10^{-11}\ M_{sun}/yr$	$6.9 \times 10^{-10}\ M_{sun}/yr$
chi^1 Ori (C)	$1.3 \times 10^{-13}\ M_{sun}/yr$	$4.2 \times 10^{-12}\ M_{sun}/yr$	$1.3 \times 10^{-10}\ M_{sun}/yr$
chi^1 Ori (Ku)	$7.2 \times 10^{-13}\ M_{sun}/yr$	$2.3 \times 10^{-11}\ M_{sun}/yr$	$7.2 \times 10^{-10}\ M_{sun}/yr$

Stellar mass loss rates

- kappa[1] Cet & pi[1] Uma (non-detections): place upper limits for mass loss rates

- assume well-collimated anisotropic ionized flow
- for *same* wind mass loss rate the outflowing gas is de
- a given radio emission requires *lower* mass loss rate

$$S_\nu = 5.1 \times 10^{11} \left(\frac{\dot{M}}{v}\right)^{4/3} T^{0.1}\ \nu^{0.6}\ d^{-2}/\theta\,(sin(i))^{1/3},$$

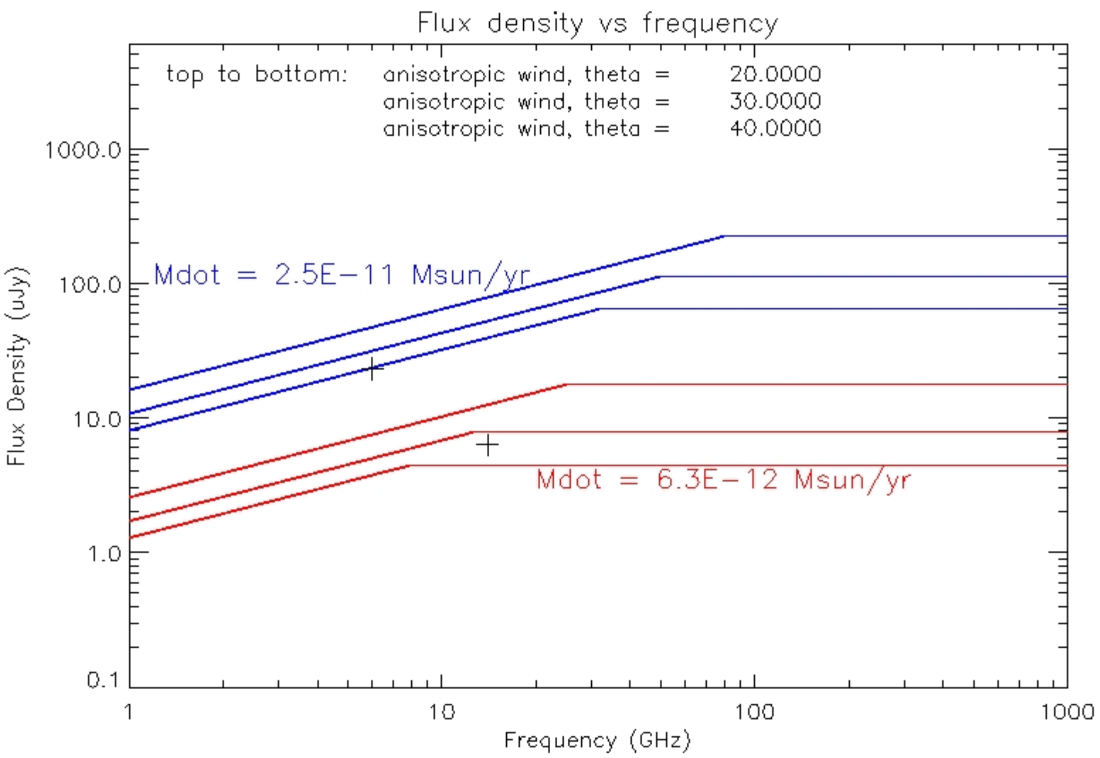


Reynolds (1986)

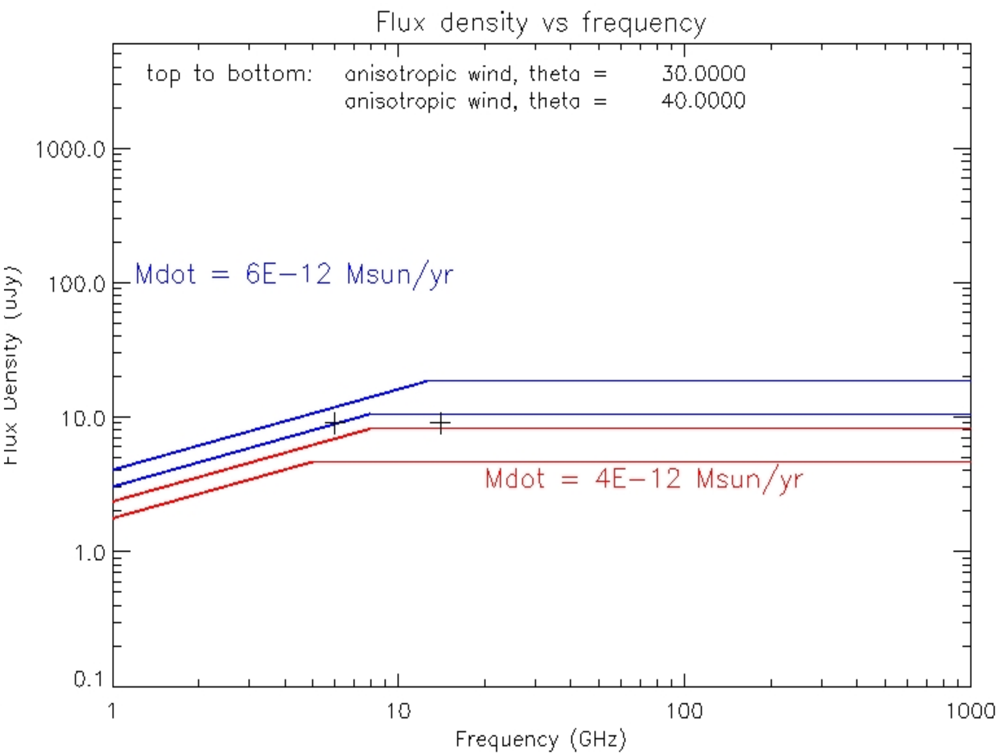
- non-detections: for ϴ = 40° and v = 400 km/s
  - π[1] UMa: $\dot{M} < 2.5\times10^{-12}\ \mathrm{M_\odot/yr}$ in C-Band
    $\dot{M} < 6.3\times10^{-12}\ \mathrm{M_\odot/yr}$ in Ku-Band
  - κ[1] Cet: $\dot{M} < 6\times10^{-12}\ \mathrm{M_\odot/yr}$ in C-Band
    $\dot{M} < 4.1\times10^{-12}\ \mathrm{M_\odot/yr}$ in Ku-Band

optically thick wind

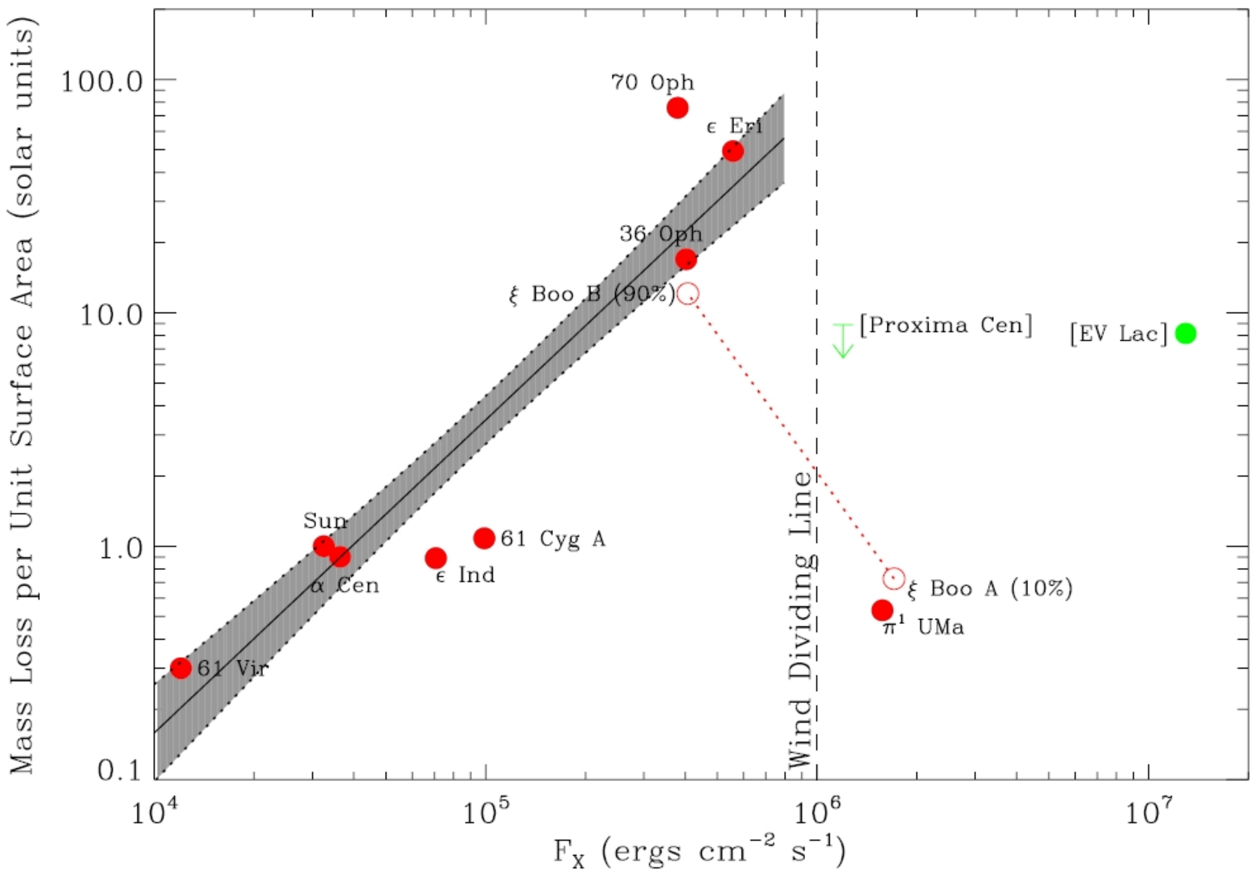
π^1 UMa



κ^1 Cet



Comparison to Lyman-α absorption



Wood et. al (2014)

For π¹ UMa:

- Wood et al. (2014) Lyman-α absorption: $\dot{M} = 0.5\ \dot{M}_{\odot}$ (rotation?)
- Drake et al (2013) considering CMEs: $\dot{M} = 150\ \dot{M}_{\odot}$
- our observation: $\dot{M} = 300\ \dot{M}_{\odot}$

Conclusions

- a higher solar luminosity for the young Sun could be possible if the initial solar mass was higher
- radio observations of young solar analogs lead to upper limits for the mass loss rate of the young Sun
- direct observations are still challenging
- trace the mass loss of the young Sun by integration back in time
- a result of 2 % would be nice