What Lynx could tell us about exoplanet habitability

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From Chandra to Lynx
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Perspective to stimulate your thoughts

- Habitability of exoplanets is arguably the most exciting aspect of astrophysics today and in the near future (time of Decade Survey).
- Conventional wisdom changes rapidly (best candidates for habitability are: Earth-like or super-Earths?, G or K or M host stars?, active or quiescent stars?
- X-ray observations have not been important tools for exoplanet studies until now, but could be in future.
- Could exoplanets be observable X-ray sources?
- Assumption: Habitability likely requires that a rocky planet retain an atmosphere (and surface water).
- What spectral resolution does Lynx need?

Outline

- Mechanisms of exoplanet atmospheric mass loss
- Why stellar EUV emission is important for thermal mass-loss processes, but hard to measure
- Stellar winds are important for non-thermal mass-loss processes, but hard to measure
- Coronal mass ejections (CMEs) are important, but hard to measure
- Energetic proton events can effect habitability, but have not been observed during stellar flares
- Conclusions: what habitability questions could Lynx address?

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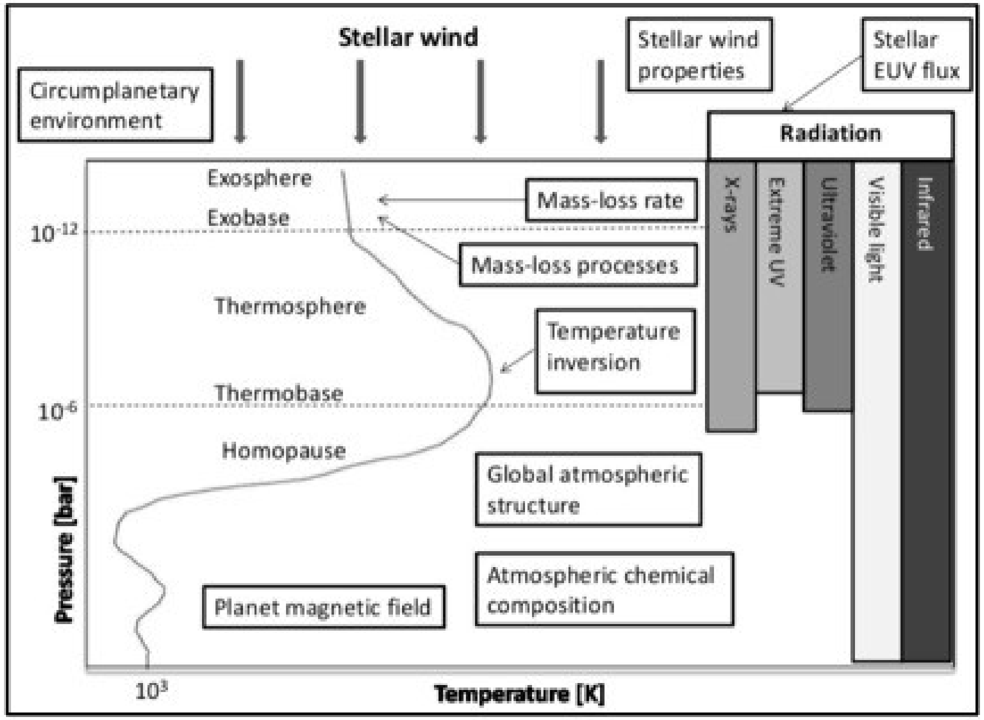
Atmospheric escape



Thermal escape

Jeans escape
(*Jeans 1925; Chamberlain 1963*)

Blow-off
(*Lammer+2003; Koskinen+2014*)

Boil-off
(*Owen & Wu 2016; Fossati+2017a*)

Non-thermal escape
(*Lammer+2013*)

– Observable only at UV wavelengths!
– Most of the escape happens when planets are young (≈500 Myr)!

iwf.oeaw.ac.at L. Fossati

Thermal mass-loss regimes (Fossati et al. A+A 598, A90 (2017))

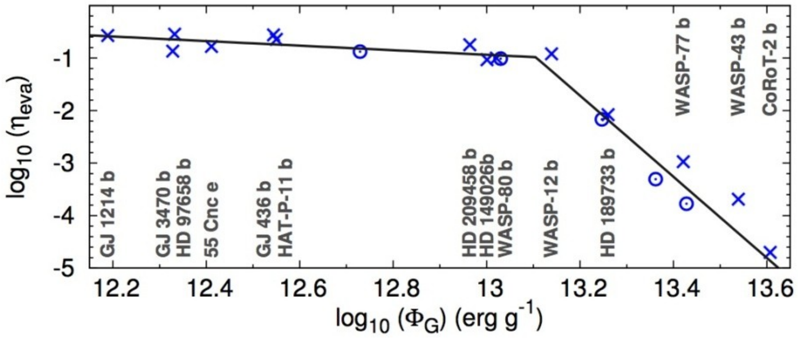
- $\Lambda = GM_{pl}m_H/k_BT_{exo}R_{pl} = (v_{esc}/v_0)^2$ = Jeans parameter
- T_{exo} is temperature at the exobase where particles can escape. Heated by stellar optical+IR or XUV radiation.
- GM_{pl}/R_{pl} = gravitational potential of the exoplanet.
- In the high velocity tail of a MB distribution, the number of particles is proportional to exp(-Λ).
- For Λ>30 and a static atmosphere, the Jeans escape rate is very slow.
- For Λ<15 and a static atmosphere, moderate "boil-off" escape rate.
- For Λ<1.5, the atmosphere is hydrodynamic with rapid escape rate in the "blow-off regime". Roche lobe overflow can increase the rate.

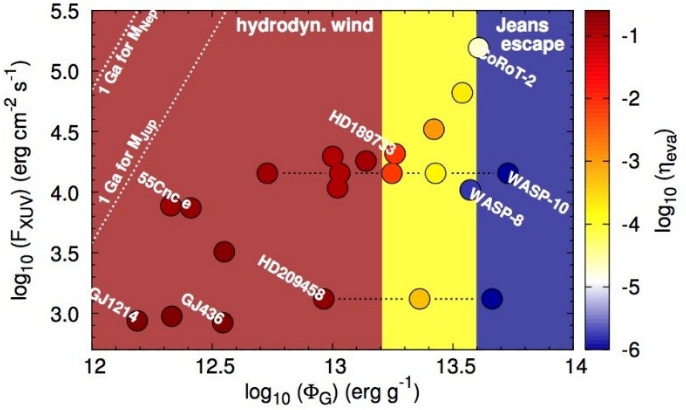
Energy-limited (thermal) mass loss

- $L_{en}=\eta \Pi R_{pl} R^2_{XUV} F_{XUV}/G M_{pl} m_H$ = escape rate
- η = efficiency factor = excess heat (after ionization of H and He) which expands the atmosphere against gravity/ total XUV input flux.
- About 15% for low gravity exoplanets (Jupiters, and mini-Neptunes).
- Can be very small for high gravity planets (rocky super-Earths) because input XUV radiation converted to UV radiation.

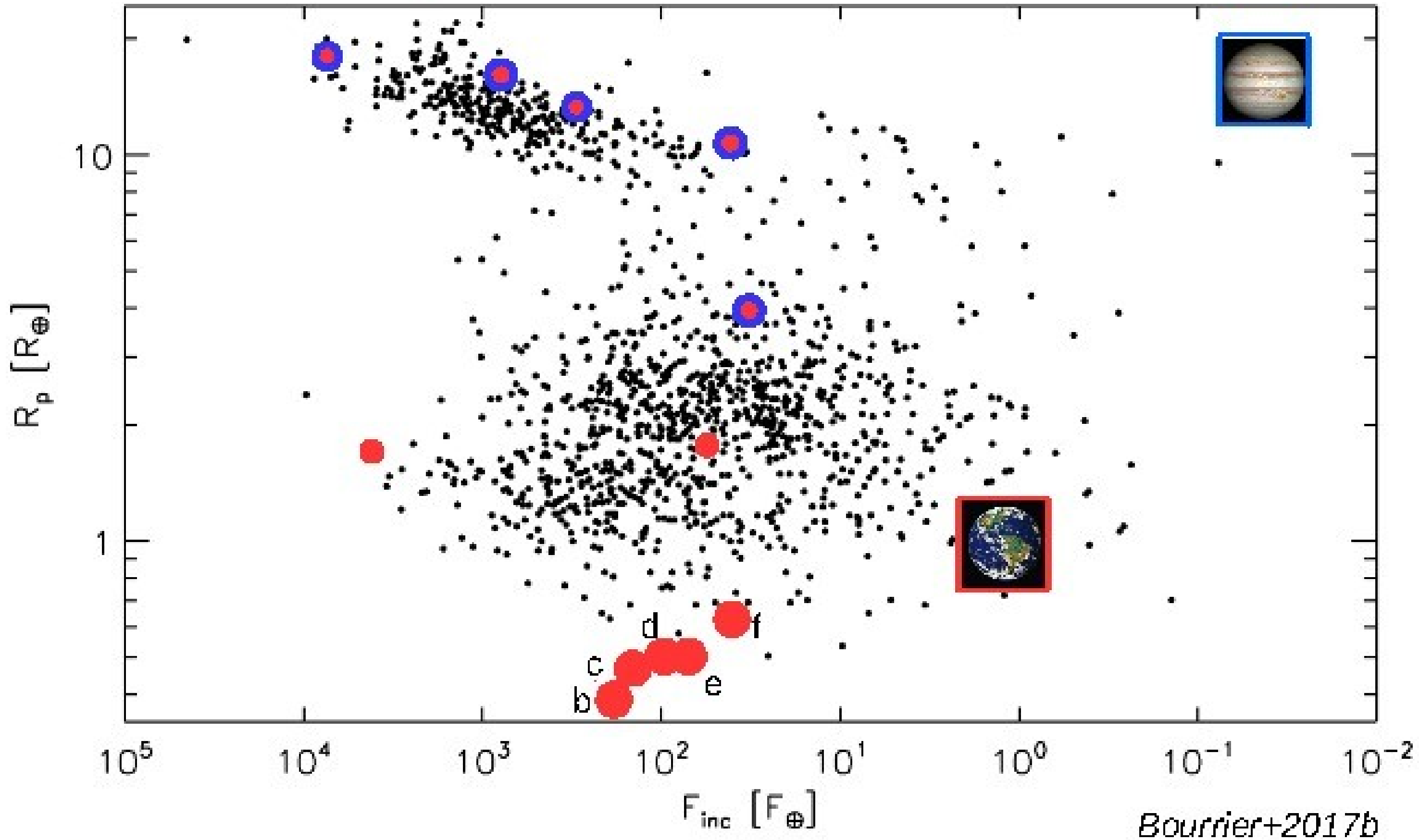
Energy-limited escape from exoplanet atmospheres: the importance of the exoplanet’s gravitational potential (Salz et al. 2016)

- η_{eva}=fraction of input EUV+X-ray energy that is converted to gravitational potential energy rather than reradiated).
- $\Phi_G=-GM_{pl}/R_{pl}$ = grav. potential
- Hydrodynamic mass-loss rate becomes large when $\Phi_G < 13.1$ (hot-Jupiters, mini-Neptunes)
- For HD209458b, mass-loss rate is 10^12 g/s (hydro) vs 1 g/s (Jeans) (Lammer 2003)
- Sharp change at $\Phi_G=13.1$





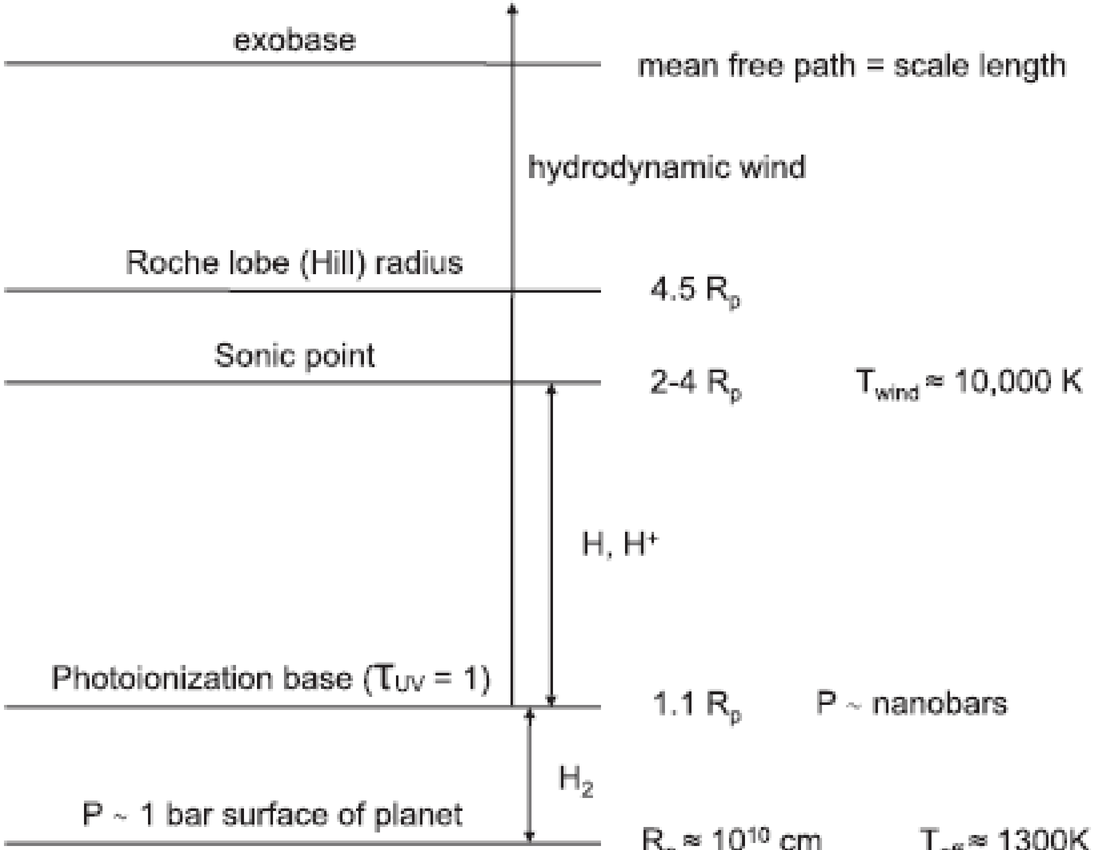
No detections of H escape: Kepler-444 b-f



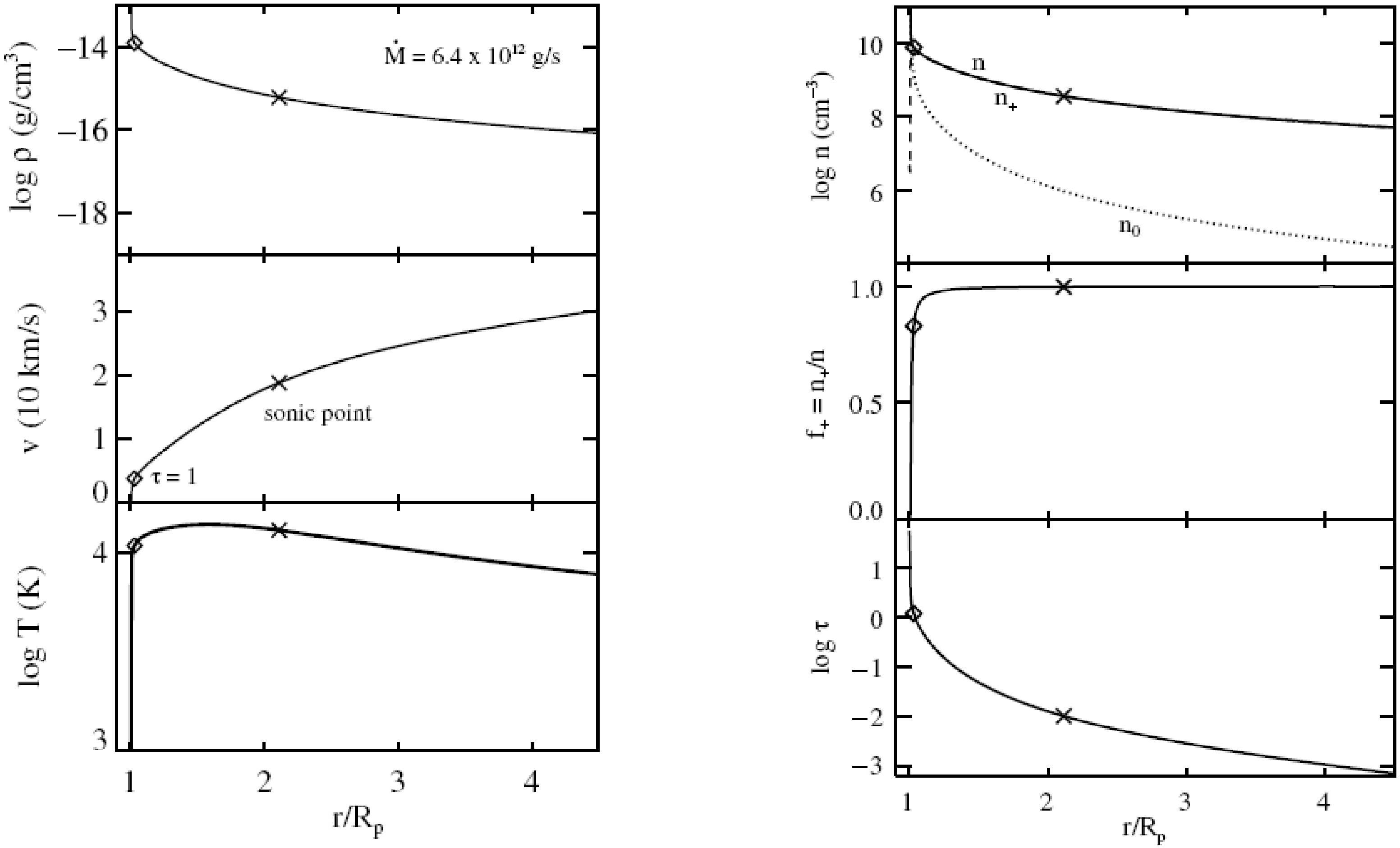
Bourrier+2017b

Atmosphere and exosphere model of HD 209458b

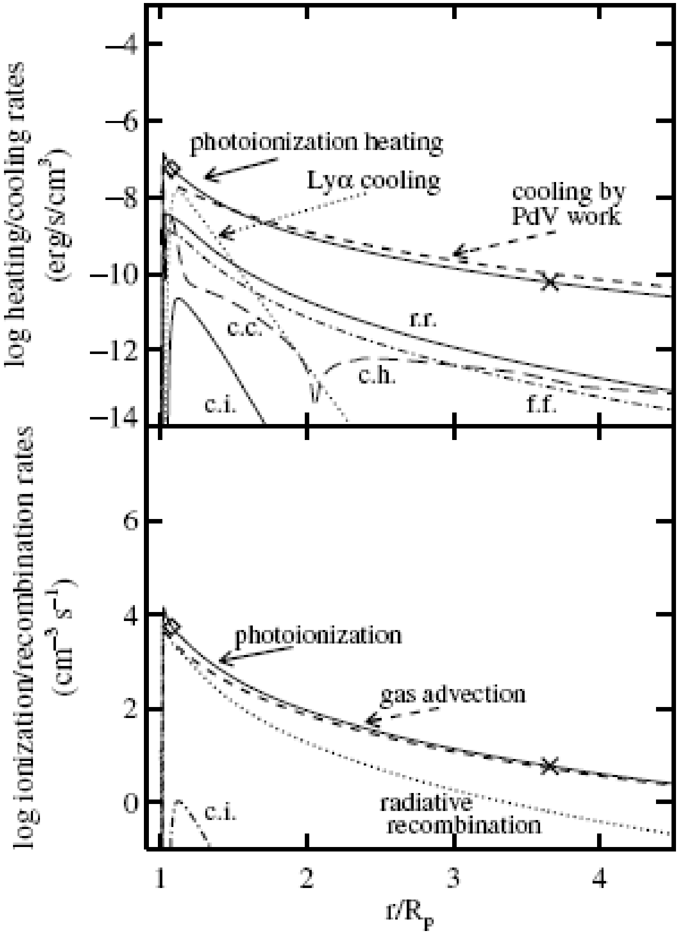
(Murray-Clay et al. ApJ 693, 23 (2009))

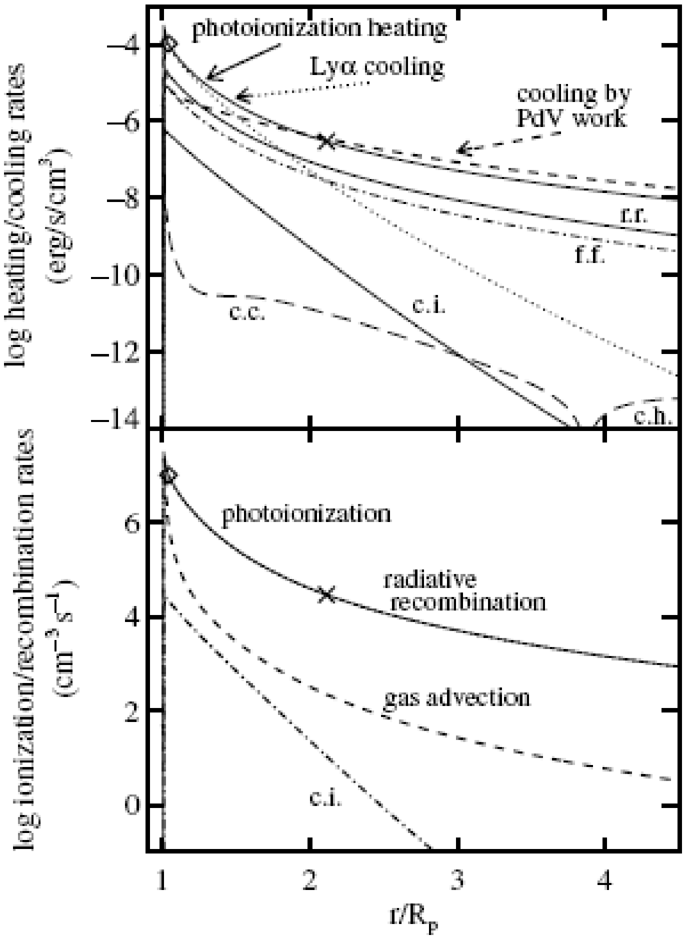


Wind model for HD 209458b assuming f(EUV)=500,000 erg/cm^2/s (1000 times larger than current Sun)



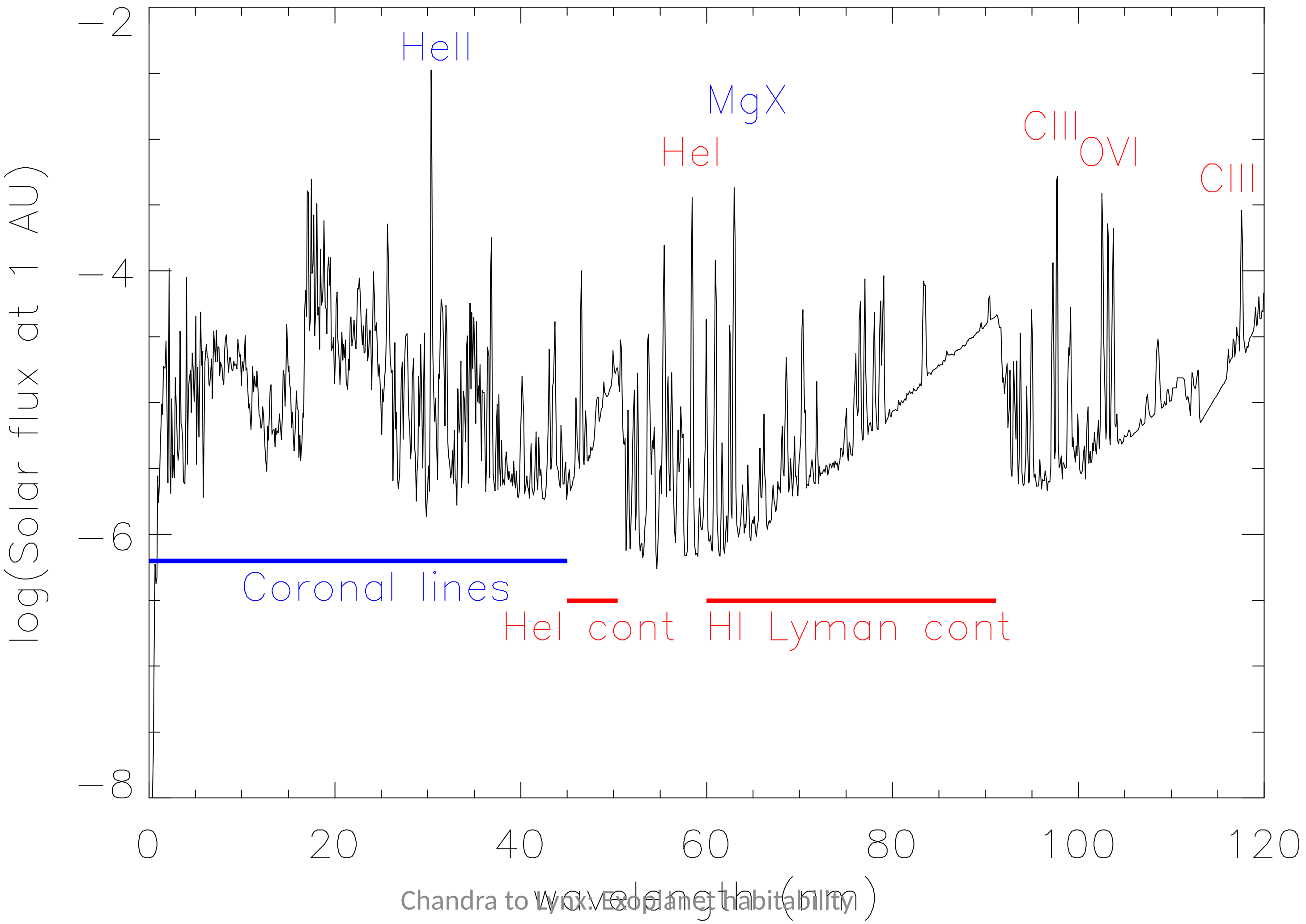
Heating/cooling/ionization for HD209458b model with f(EUV)=450 (left) and 500,000 (right)



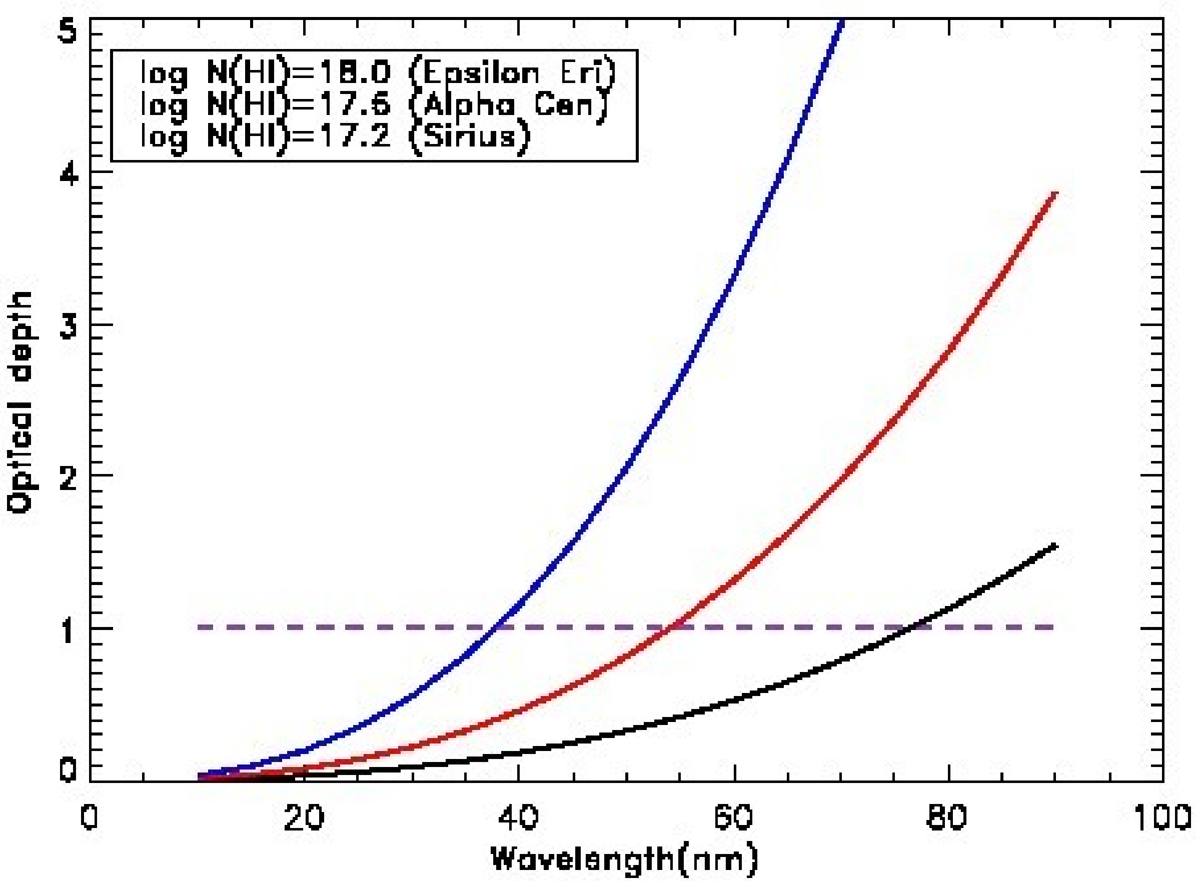


Why stellar EUV emission is important for assessing mass loss from exoplanet atmospheres, but hard to measure

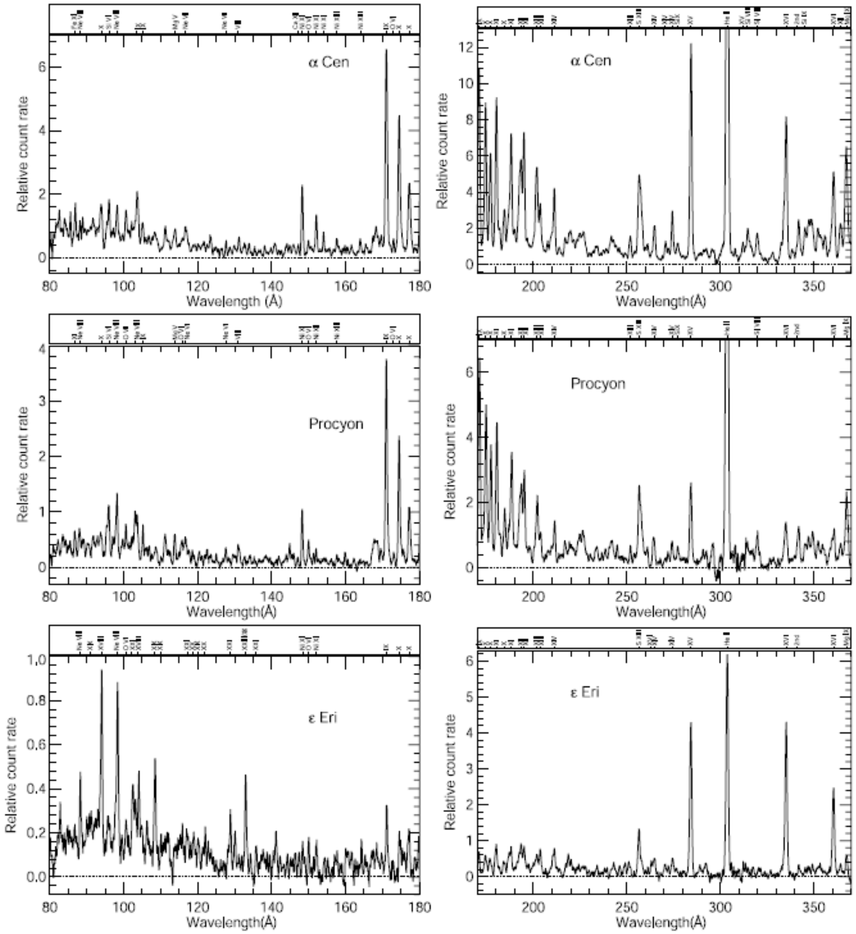
Extreme-ultraviolet (EUV) Portion of the Quiet Sun Spectrum



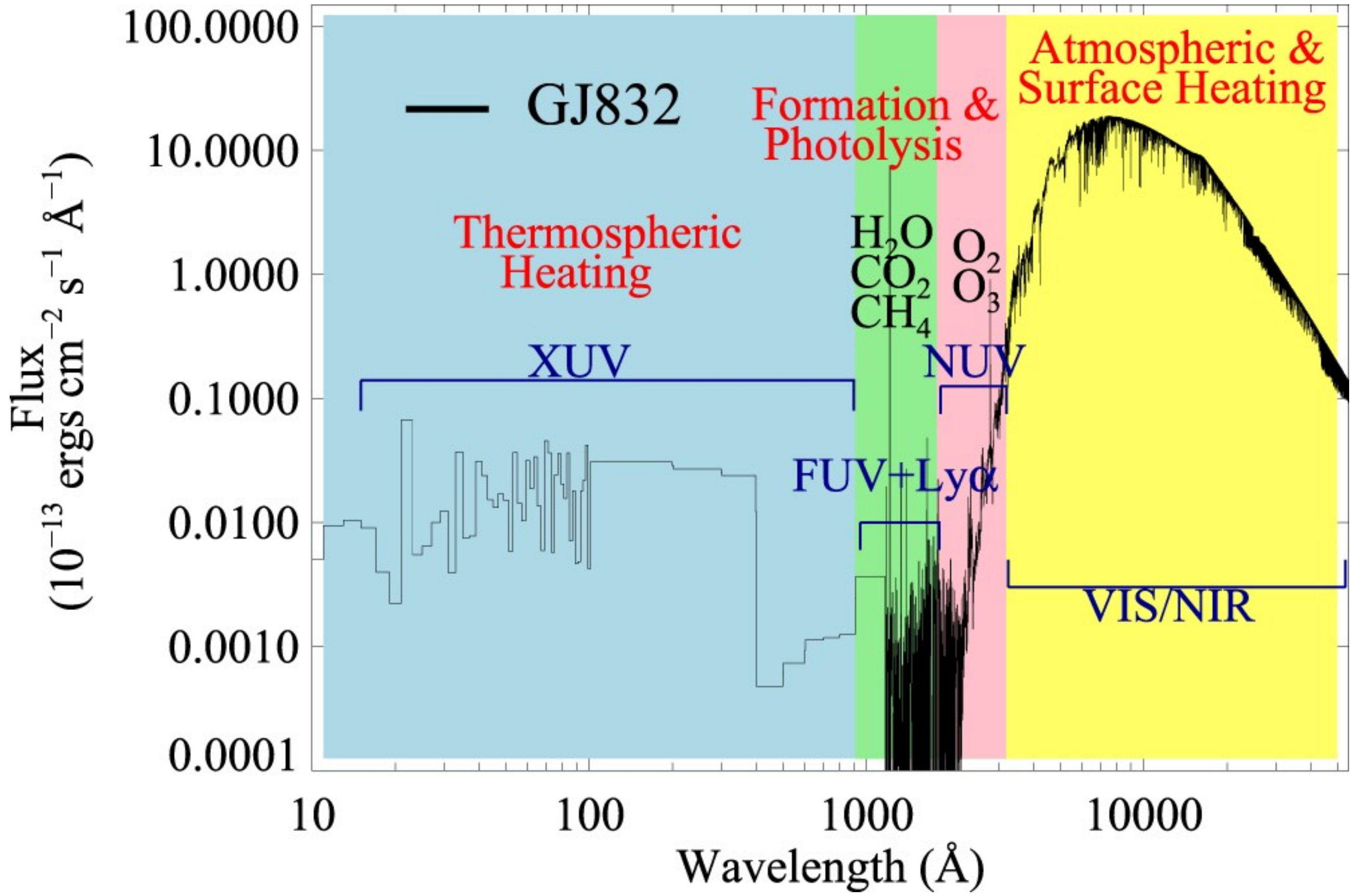
Effect of ISM opacity on EUV transmission: Line of sight to Sirius (2.6 pc) has the lowest known N(HI) and Epsilon Eri (3.2 pc) has a typical N(HI) for nearby stars



EUVE spectra of F5-K2 stars (Sanz-Forcada et al. ApJS 145,147 (2003))

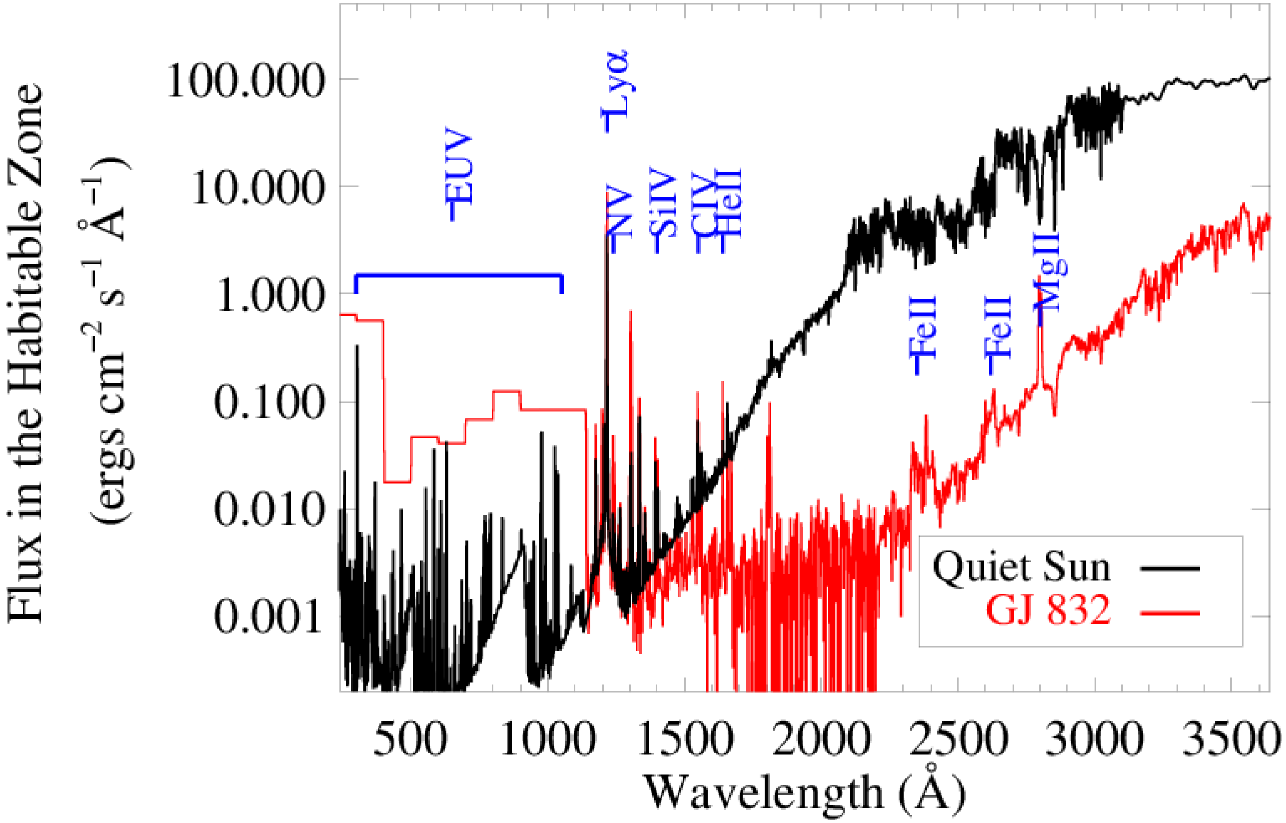


COS+ Chandra+optical spetrum of an M1.5 V star (France et al. 2016)



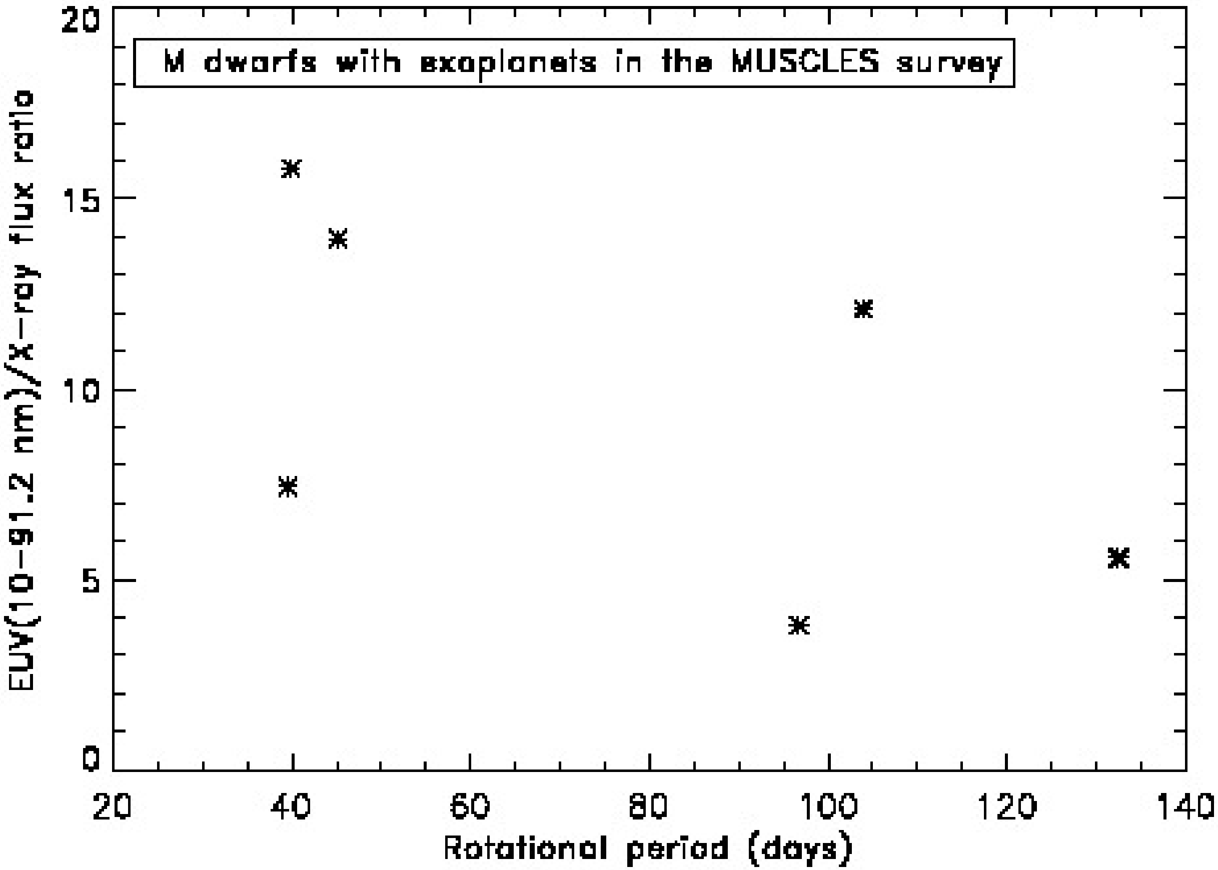
Spectral Energy Distribution

- Sun (G2 V) vs. GJ 832 (M1 V) in habitable zone

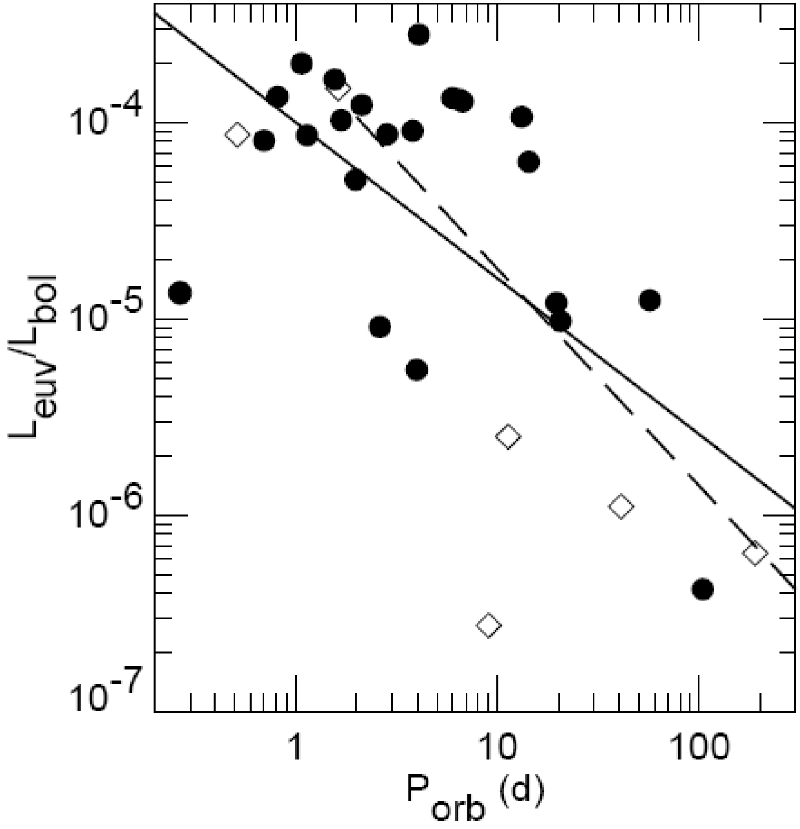


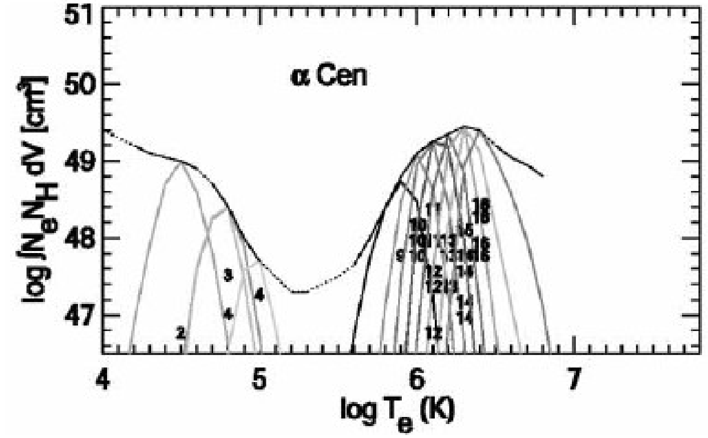
France et al. (ApJL-2012c, ApJ-2016)

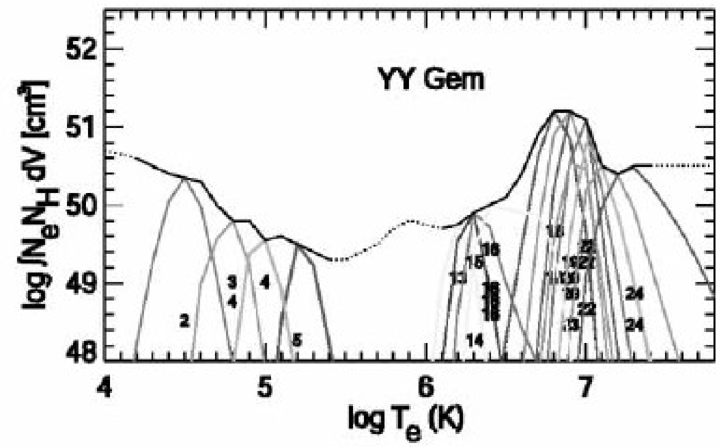
The EUV flux (10-91.2 nm) is typically 10 times larger than the X-ray flux for moderately active M dwarf stars with exoplanets



Scaling of EUV flux from X-ray and UV observations using emission measure distributions (Sanz-Forcada et al. 2003)





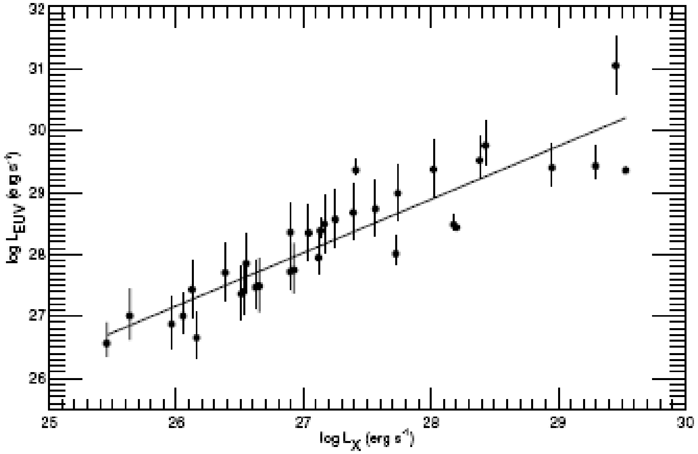


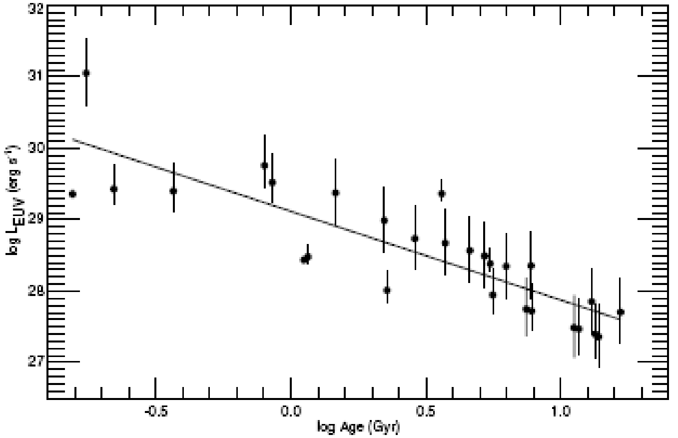
Lynx can better sample the intermediate temperature EMD.

Scaling of EUV flux from observed X-ray flux (Sanz-Forcada et al. (A+A 532, A6 (2011))

- Compute coronal models for 82 host stars.
- XUV flux (0.1-91.2 nm) computed from the emission measure distributions.
- Problem: EMD is 1-D but stellar coronae are 3-D.
- Problem: Need to include Lyman continuum.

$$L_X = 6.3 \times 10^{-4}\, L_{\rm bol} \qquad (\tau < \tau_i)$$
$$L_X = 1.89 \times 10^{28}\, \tau^{-1.55} \qquad (\tau > \tau_i),$$
$$\tau_i = 2.03 \times 10^{20}\, L_{\rm bol}^{-0.65}.$$



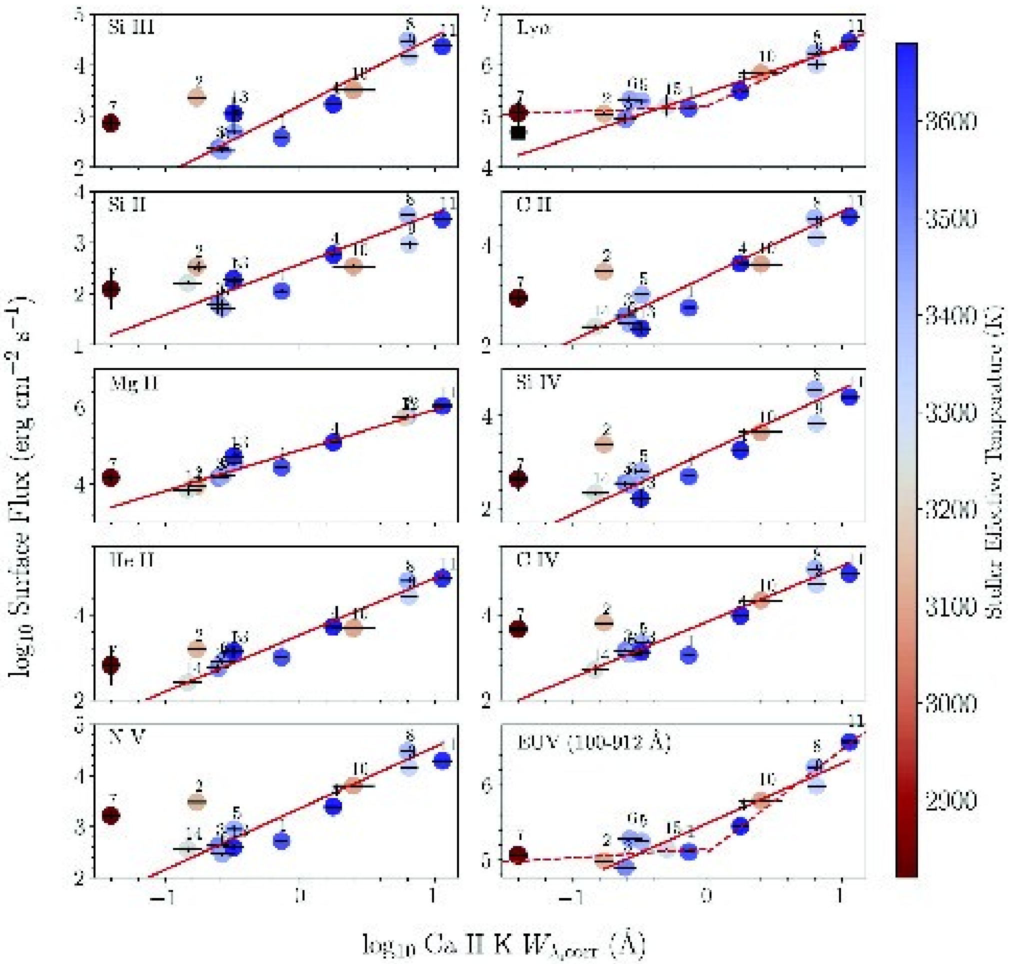


Separate the EUV into wavelength bands with different techniques for testing (Linsky et al. ApJ 766, 69 (2013))

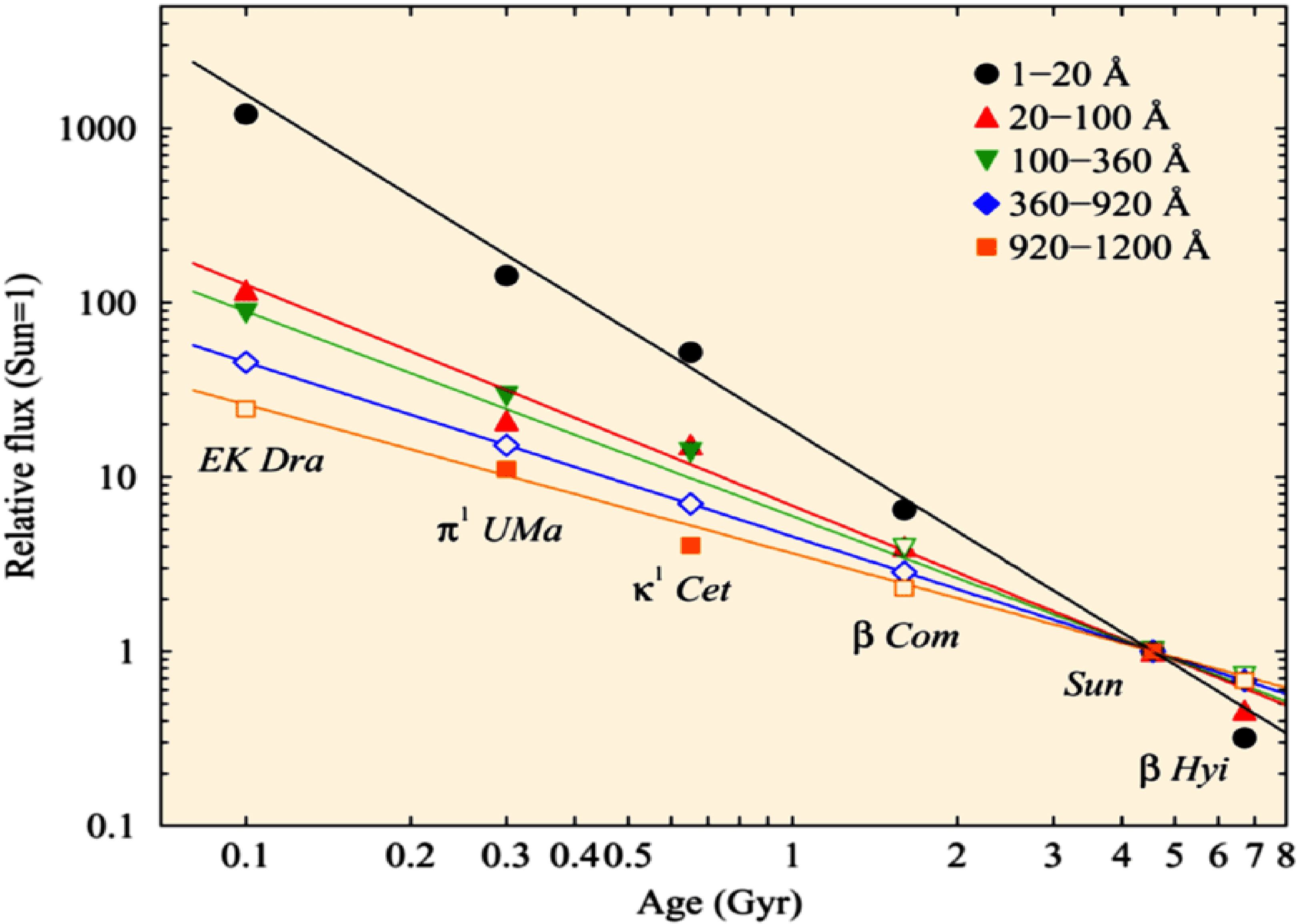
- 91.2-117 nm – H I Lyman series, C II, C III, and O VI emission lines. Little ISM absorption. Test with FUSE spectra of 5 dwarf stars.
- 70-91.2 nm – H I Lyman continuum and TR emission lines. ISM opaque so only solar data.
- 40-70 nm – Coronal and TR lines. He I and II lines and continuum. ISM opaque so only solar data.
- 10-40 nm – Coronal lines and continuum. ISM partly transparent so test with EUVE spectra of 5 stars.
- Method: Ratio all fluxes to Lyman-α to minimize dependence on activity, time variability, and spectral type. Then use correlations of Lyman-α to other observables like Ca II H+K.

Correlation of UV emission lines and EUV flux with CaII K line equivalent width

- Note positive correlation of EUV flux with CaK and other UV emission lines.
- Youngblood et al. (2017)



Does Age control X-ray and EUV Flux?



Ribas et al. 2005, ApJ, 622, 680

Stellar winds are important for estimating mass loss from exoplanet atmosphere, but are hard to measure

Thermal and wind escape rates from Mars in the present and past beginning at 3.9 Gyr (Lammer et al. 2003)

Nonthermal mass loss processes

- Photodissociation of H_20 followed by charge exchange between solar wind ions and atmospheric H, H_2 and O produces H^+ and H_2^+ and O^+ that are picked up by the magnetic field in the wind.
- Dissociative recombination leads to hot O atoms that escape: $O_2^+ + e^- \rightarrow 2O$.
- Sputtering: kinetic energy from impact of solar wind particles kicks out O, CO and CO_2.
- O also oxidizes the surface rocks.
- Total loss of H_2O equivalent to an ocean covering all of Mars to 12m depth.

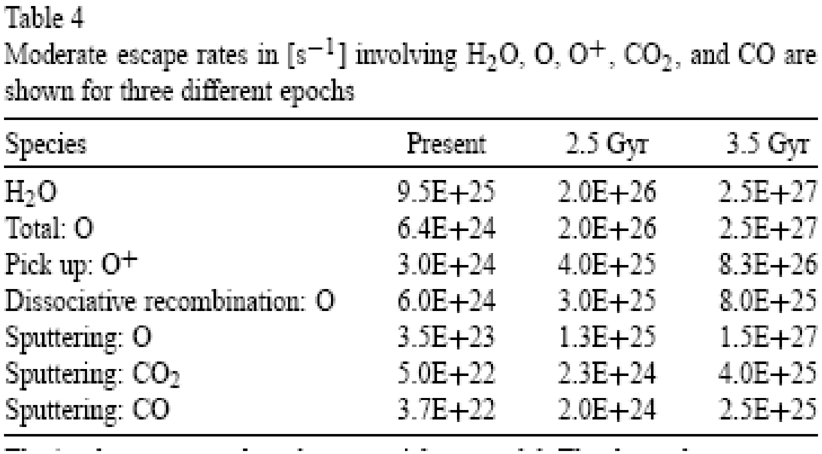


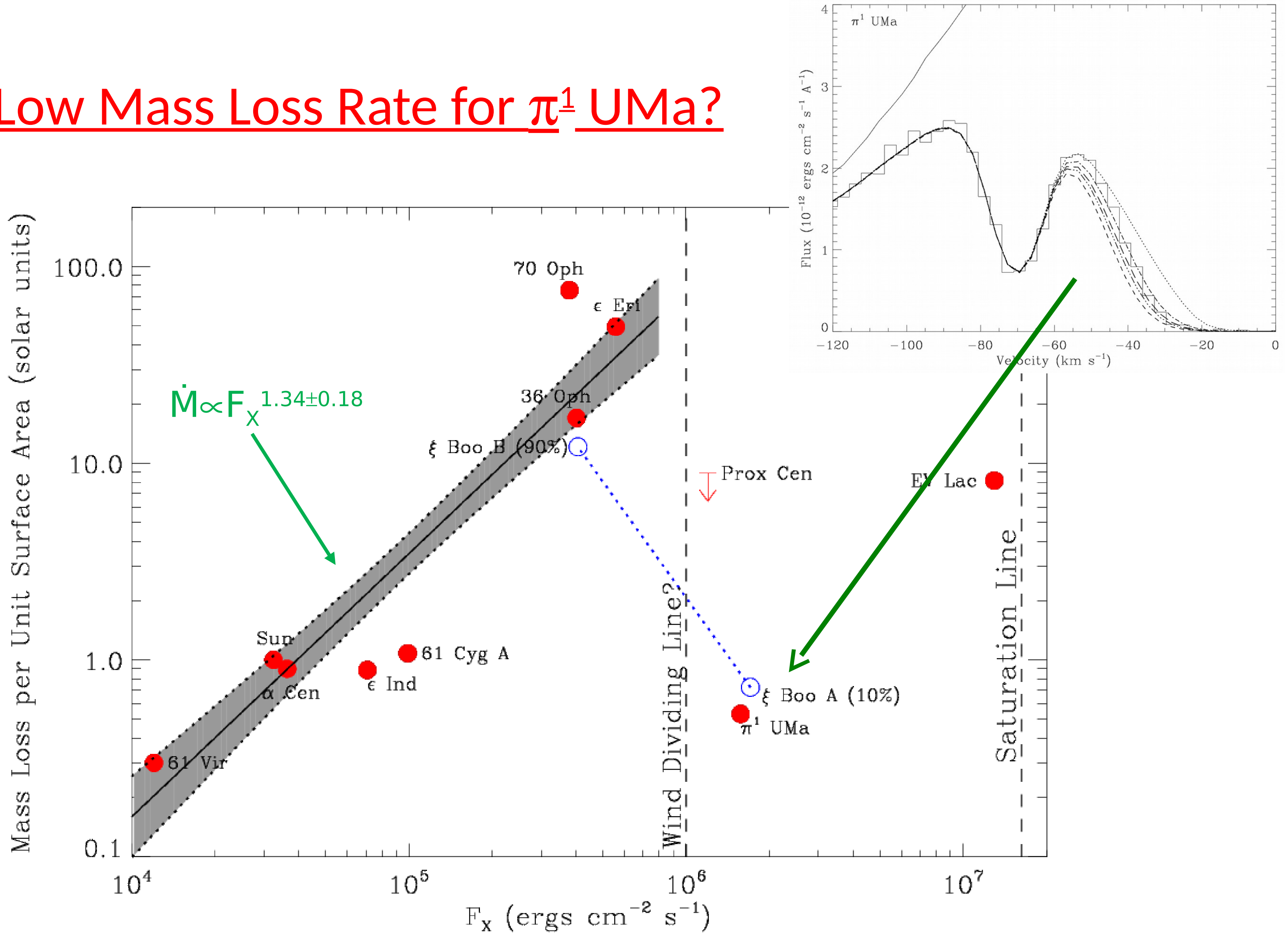
Table 4

Moderate escape rates in [s^{-1}] involving H_2O, O, O^+, CO_2, and CO are shown for three different epochs

Species	Present	2.5 Gyr	3.5 Gyr
H_2O	9.5E+25	2.0E+26	2.5E+27
Total: O	6.4E+24	2.0E+26	2.5E+27
Pick up: O^+	3.0E+24	4.0E+25	8.3E+26
Dissociative recombination: O	6.0E+24	3.0E+25	8.0E+25
Sputtering: O	3.5E+23	1.3E+25	1.5E+27
Sputtering: CO_2	5.0E+22	2.3E+24	4.0E+25
Sputtering: CO	3.7E+22	2.0E+24	2.5E+25

Thermal mass loss from heating of outer atmosphere by solar EUV and X-ray flux leading to the escape of light particles (H and H_2). Jeans escape process is when particles in the high energy Maxwell-Boltzmann tail have enough kinetic energy to escape gravity. Hydrodynamic blow-off when large mass loss rates.

A Low Mass Loss Rate for π¹ UMa?



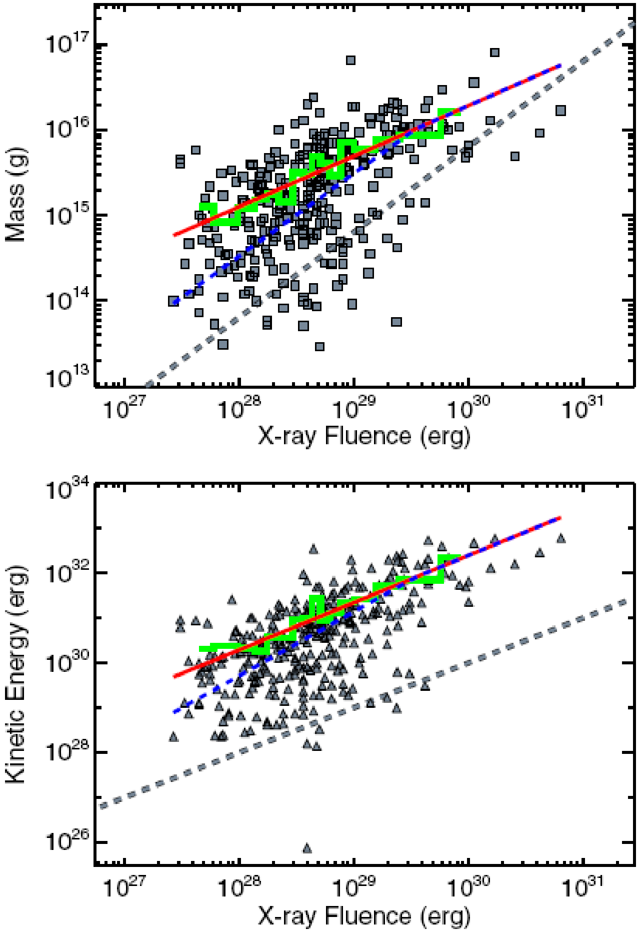
$\dot{M} \propto F_X^{1.34\pm0.18}$

Wood et al. 2005, ApJ, 628, L143; Wood et al. 2010, ApJ, 717, 1279

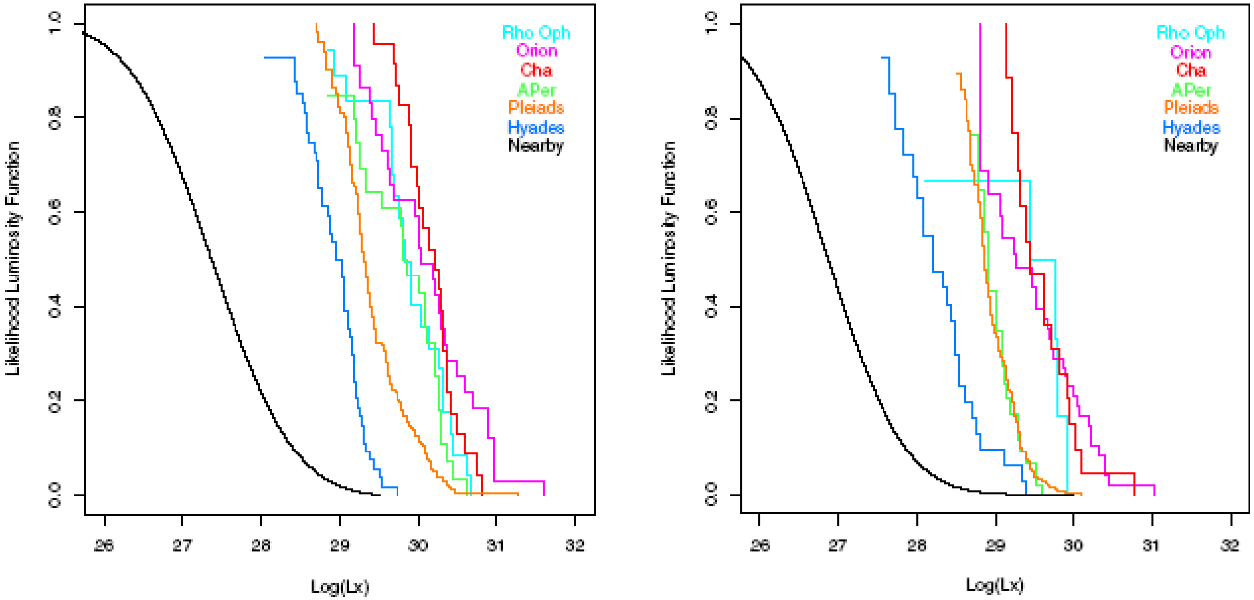
Stellar coronal mass ejections (CMEs) are critical for assessing habitability but are difficult to observe – what Lynx can do to observe and assess stellar CMEs

Could mass loss in coronal mass ejections (CMEs) dominate the total mass loss for active stars?

- Drake et al. (ApJ 764, 179 (2013)) proposed an $\dot{M}_{\mathrm{CME}}$ vs L_x correlation based on solar data for CME mass and X-ray energy and a power law distribution of solar flare energies.
- Dashed line (upper plot) is $\dot{M}_{\mathrm{CME}}=10^{-10}\,(L_x/10^{30})\,M_{sun}/\mathrm{yr}$.
- Red line (lower plot) is $KE_{CME}=200L_x$ (most CME and flare energy is kinetic not X-rays!)



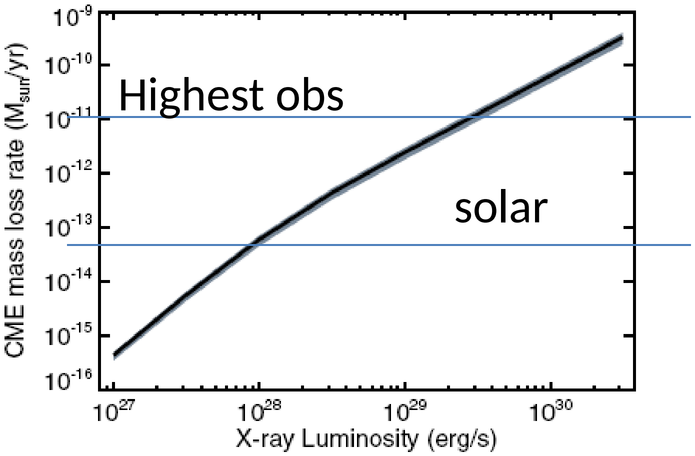
X-ray luminosity functions for groups of stars with increasing age (see Güdel 2004)

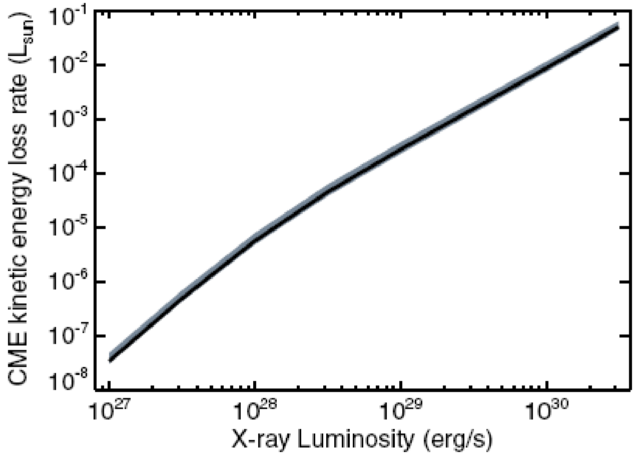


- Decrease in luminosity function (fraction of stars with X-ray luminosities $>L_x$) for star groups with increasing age (from young clusters → Pleiades → Hyades → Field).
- Left: masses 0.5 to 1 M_{sun}; right: 0.25 to 0.5 M_{sun}.
- Sun: 26.35 (min), 26.8 (max), Carrington flare peak 28.2
- Giant flares on DG CVn (M dwarf binary): 32.3 and 32.65

Implications of the CME mass loss rates

- Assume a power-law distribution of CMEs, $dn/dE=kE^{-\alpha}$
- $\dot{M}$CME~ 5x10^{-10} M$_{sun}$/yr and E$_{KE}$~0.1L$_{bol}$ predicted for active dwarf stars (HUGE!).
- $\dot{M}$CME=4x10^{-16}M$_{sun}$/yr predicted for the Sun (2% of observed solar $\dot{M}$). L$_x$~10^{27} for the active Sun,
- $\dot{M}_{CME}$ increases with L$_x$ relative to steady mass loss rates.
- Efficiency of conversion of L$_{bol}$ to kinetic energy must limit the energy in mass loss to 0.01-0.001 L$_{bol}$ and thus limit $\dot{M}$CME. For the Sun efficiency is 0.5x10^{-6}.





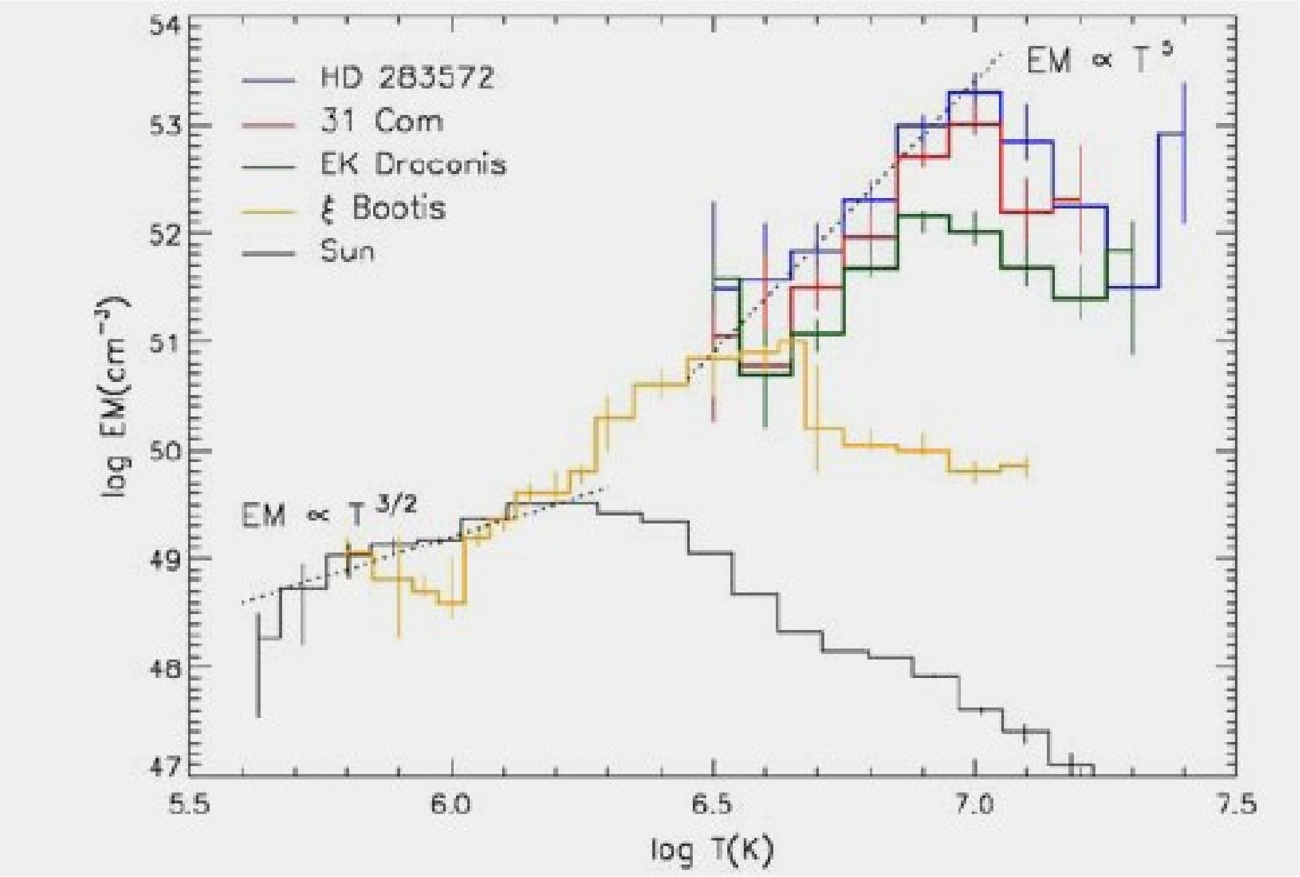
Could strong magnetic fields on active stars prevent CMEs?

- Most strong flares on Sun have associated CMEs with more energy that in X-ray+EUV emission.
- Simple extrapolation of solar CME properties to active star X-ray flare rates and energies has led to unrealistically high mass-loss rates (Drake et al. 2013).
- Strong large-scale magnetic fields (measured) on active stars could force the flaring plasma to follow closed field lines.
- See simulations by Alvarado-Gomez et al. poster.
- Unexpected conclusion: Stellar activity enhances habitability?

The effects on an Earth-like exoplanet in the HZ of AD Leo (dM3.5) from its April 12, 1985 flare

- Segura et al. (Astrobiology 10, 751 (2010)) simulation of the effect of this powerful flare on an exoplanet (with an Earth-like atmosphere) in its HZ (0.16 AU from star).
- Simulation of a direct hit by an energetic proton event 200 times more powerful than the 1859 Carrington event.
- UV radiation alone decreases ozone column depth by 1% near flare peak with recovery in 1 day.
- If energetic protons (10 MeV) are correlated with impulsive X-ray flux (like Sun), then N oxides deplete 94% of ozone for 50 yr, leading to penetration of strong UV radiation down to surface of exoplanet.
- But exoplanet’s magnetic field, sum of many events, and uncertain correlation for M stars.
- Lynx needs to study impulsive phases of M dwarf flares to look for ejection of the hottest gas which could be evidence of 10 MeV protons.

Emission measures of G stars with increasing rotation rate and decreasing age (Güdel+Yaze 2009)

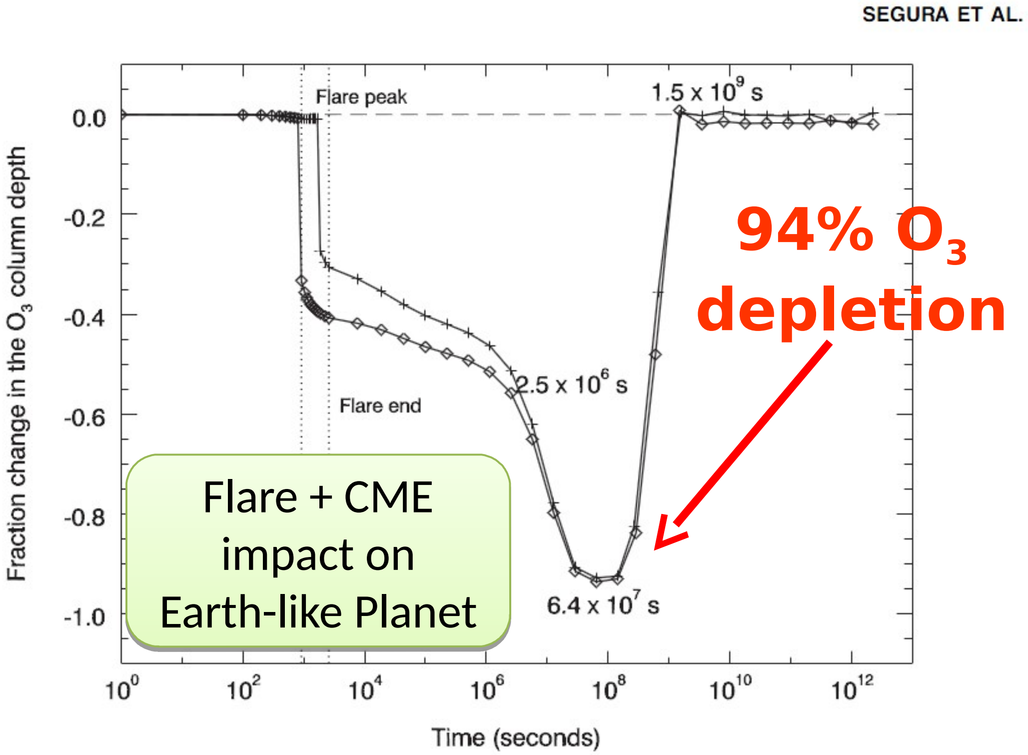


Atmospheric Impacts and Potential Biomarkers

- Tian et al. (2014); possible abiotic O_2 and O_3
- Domagal-Goldman et al. (2014); possible abiotic O_3
- Rugheimer et al. (2015); FUV/ NUV irradiances from active/inactive stars vs. stellar models and Earth-like planet spectra

- Segura et al. (2010); atmospheric (O_3) depleted from strong M dwarf flares by protons forming NOx that destroy ozone.

See also Airapetian et al. (2016): strong flares generating greenhouse gases and prebiotic chemistry on early Earth.

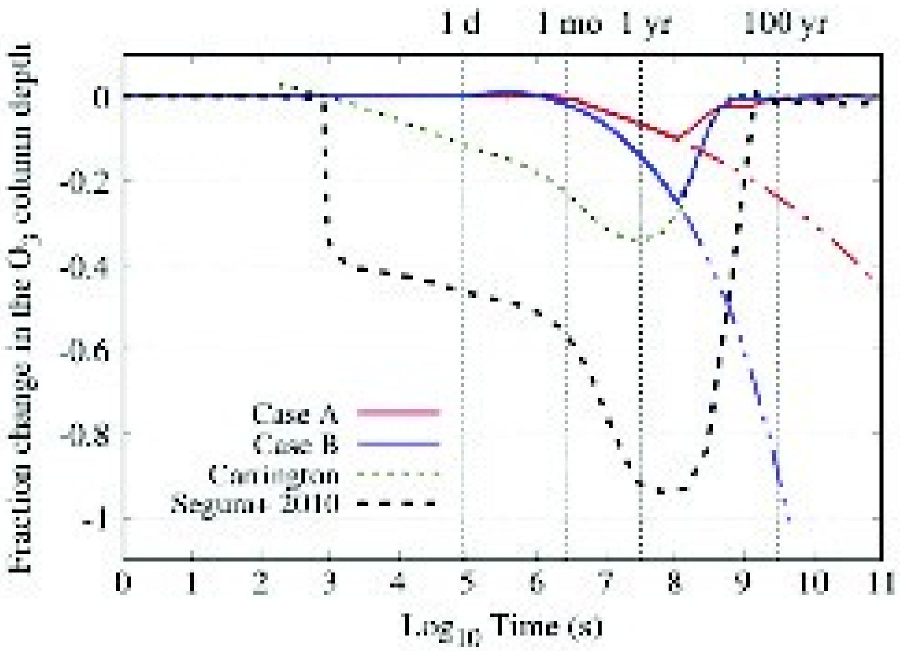


94% O_3 depletion

Flare + CME impact on Earth-like Planet

Fractional change in the ozone optical depth on a terrestrial planet with an Earth-like atmosphere and no magnetosphere

- Case A: multiple proton events (1 every 12 hr with 1200 pfu) hitting a planet in the HZ (0.18 AU) of GJ 876.
- Case B: same but 1 event every 2 hours.
- A single Carrington proton event (6.3x10^6 pfu) hitting a planet at 0.18 AU.
- A single AD Leo giant event (5.9x10^8 pfu) at 0.16 AU.



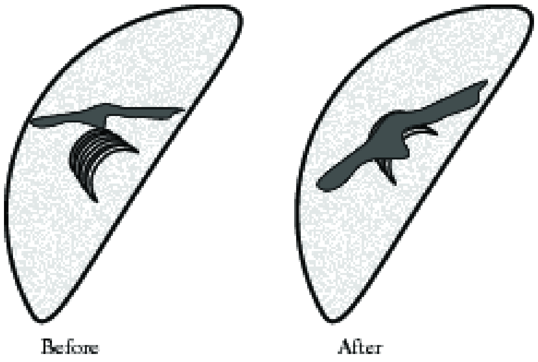
Youngblood et al. (ApJ 843, 31 (2017))

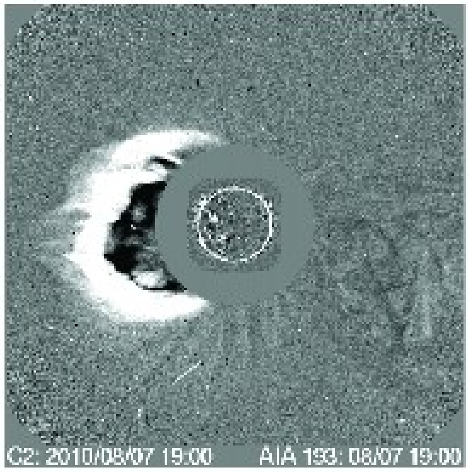
How can Lynx detect and characterize stellar CMEs and ejected coronal plasma?

By X-ray dimming and Doppler spectroscopy

Solar dimming mechanisms (Mason et al. 2014) as indicators of CME ejections

- Obscuration dimming (upper right). Prominence (CME) moves across line of sight to the flare producing absorption
- Mass-loss dimming (lower right) due to ejection of coronal mass (CME?).
- Thermal dimming
- Wave dimming
- Doppler dimming
- Bandpass shift dimming
- All of these mechanisms have been observed in solar EUV data with different spectral signatures.

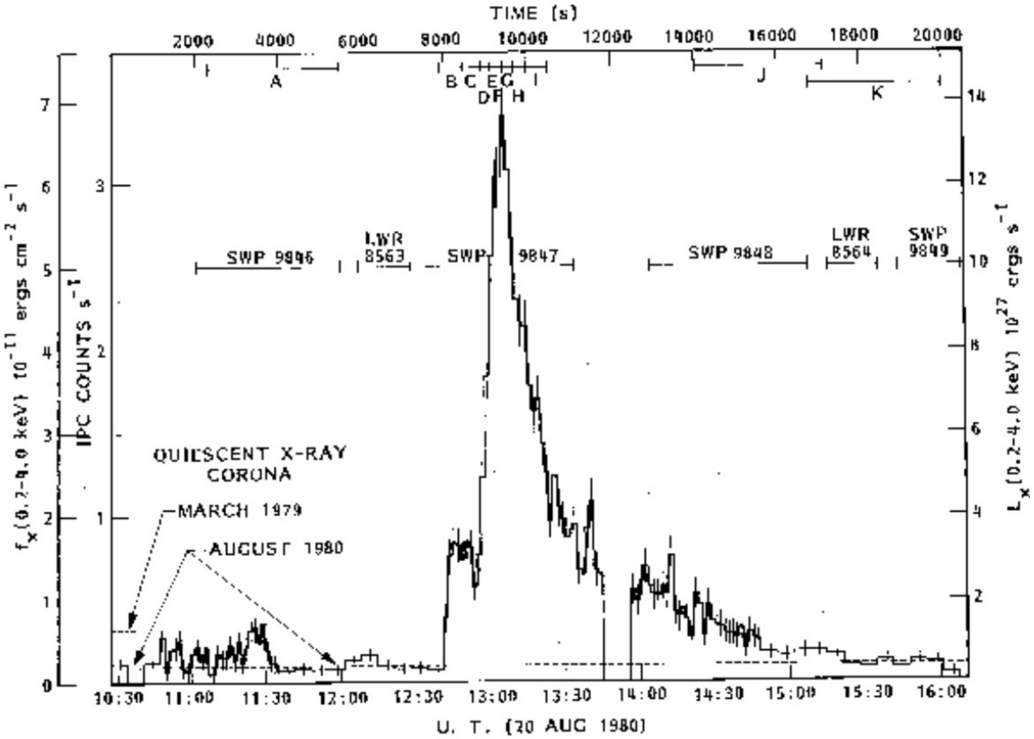




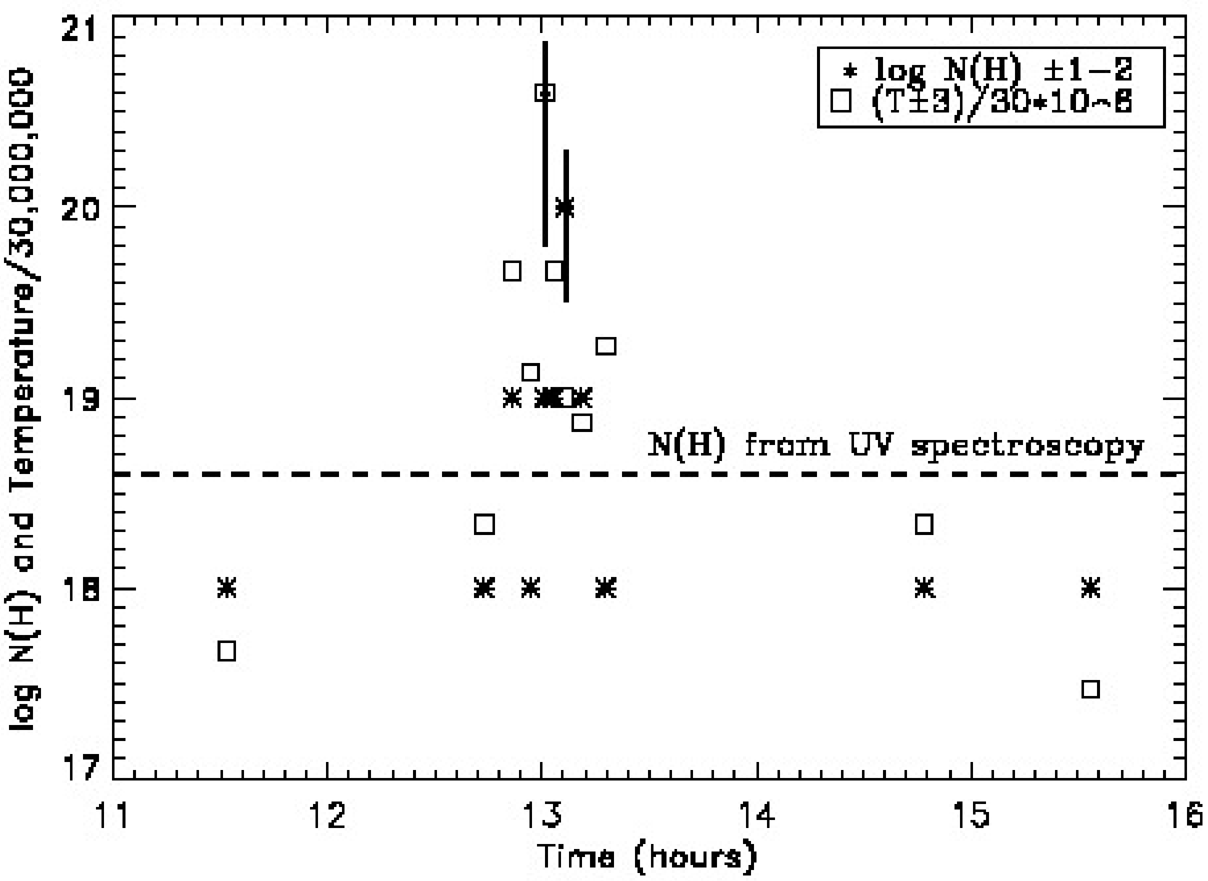
CME expansion velocity 871 km/s

Flare observed on Prox Centauri by Haisch et al. (ApJ 267, 280 (1983))

- X20 two-ribbon solar-like flare on Prox Cen observed on 20 Aug 1980 by Einstein and IUE.
- Peak Lx~2x10^28 erg/s, T~27x10^6 K, Lx/Lbol~100 times solar ratio.
- Total flare energy E~2x10^31 ergs
- Commonly seen X-ray light curve except for very low X-ray flux during a 4 minute time interval.



Plot of log N(H) and coronal temperature during the Proxima Cen flare



Possible interpretation of the increase in N(H) during the Prox Cen flare

- Haisch et al. (1983) describe the Prox Cen flare as similar to solar long duration two-ribbon flares that often have prominence eruptions.
- N(H) increase inferred from decrease in X-ray flux in lowest energy channels.
- Log N(H) = 20 consistent with solar-type prominence with scale about a stellar radius expanding at 500 km/s.

"It is possible in the light of this picture to attribute the temporary increase in N(H) observed in the Proxima Cen event to the passage of cool, dense prominence material across our line of sight, thus temporarily obscuring the X-ray event. This is admittedly a speculative interpretation."

Advantages of Lynx for detection of stellar CMEs and ejected coronal plasma by X-ray dimming and coronal spectroscopy

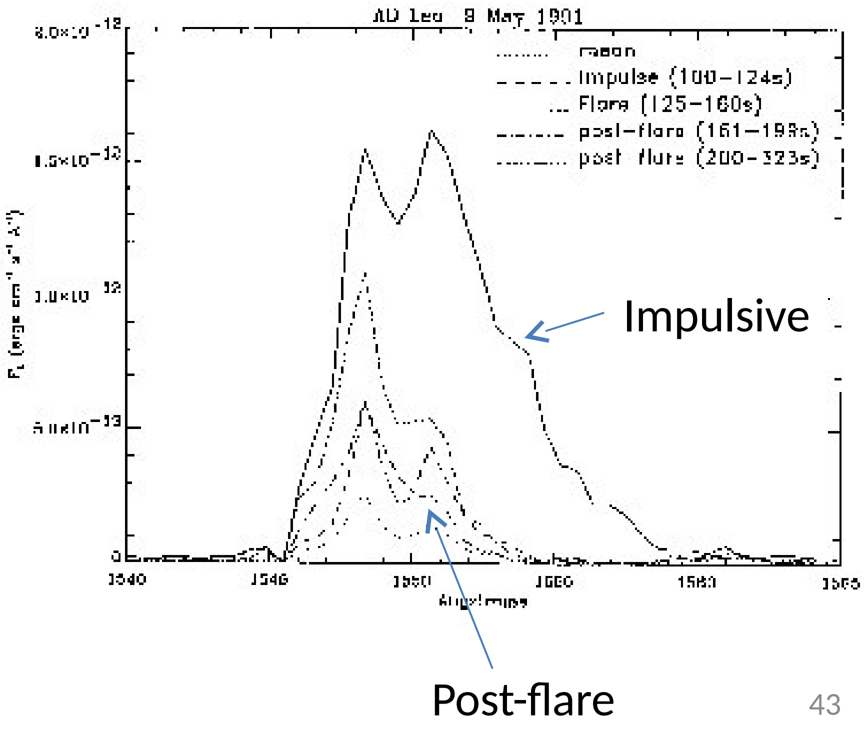
- High throughput allows high time resolution and far better S/N spectra.
- High spectral resolution (30 km/s?) permits clean measurements of Doppler shifts.
- The combination of high throughput and high spectral resolution facilitates measuring Doppler shifts of emission lines formed over a wide range of temperature at the same time.

Other evidence for stellar CMEs

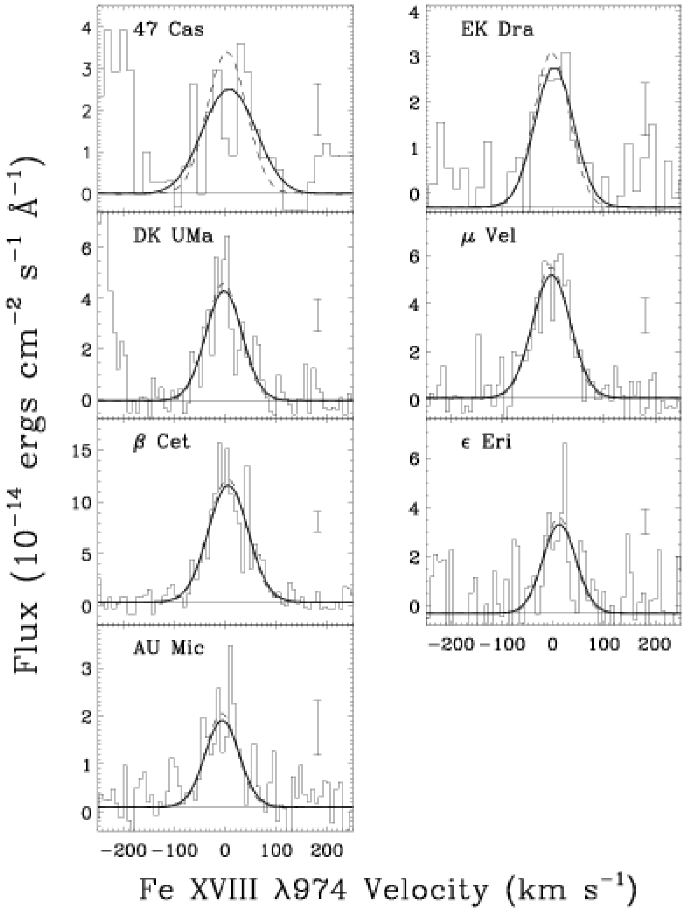
- Blue-shifted emission seen in Balmer lines during large flares on M dwarfs: e.g., flare on AD Leo (Houdebine et al. 1990) with 80A blue-shifted emission in Hγ and Hδ implying 5800 km/s outflow with E~5x10^34 erg.
- Existing searches for Type II low-frequency radio bursts indicating coronal plasma outflows .
- Why not search for outflows of coronal plasma at wavelengths of coronal emission?

UV spectra of transition region lines during large stellar flares

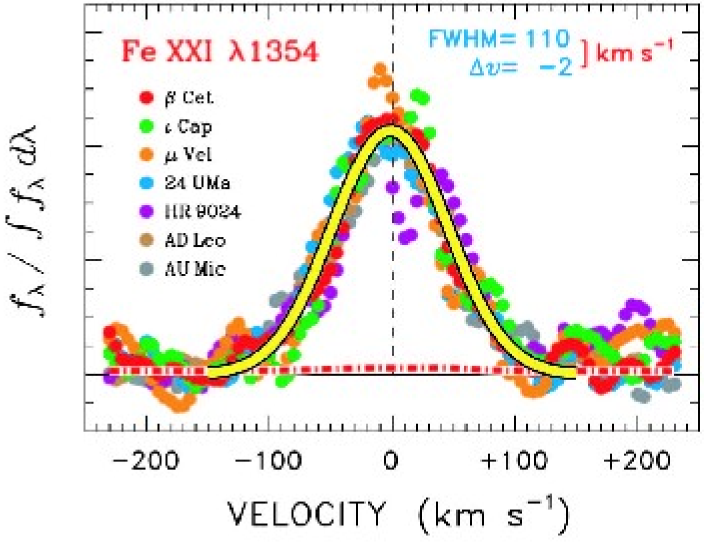
- HST/HRS spectra of the C IV emission lines (1548, 1550A) during a massive flare on AD Leo (M3.5 V)
- Maximum redshift of 1800 km/s, then steady decrease after the flare peak.
- Bookbinder et al. (Cool Stars VII 1992).
- No observed change in the blue side of the CIV lines during the flare.



Examples of coronal emission lines observed in the UV by FUSE and HST

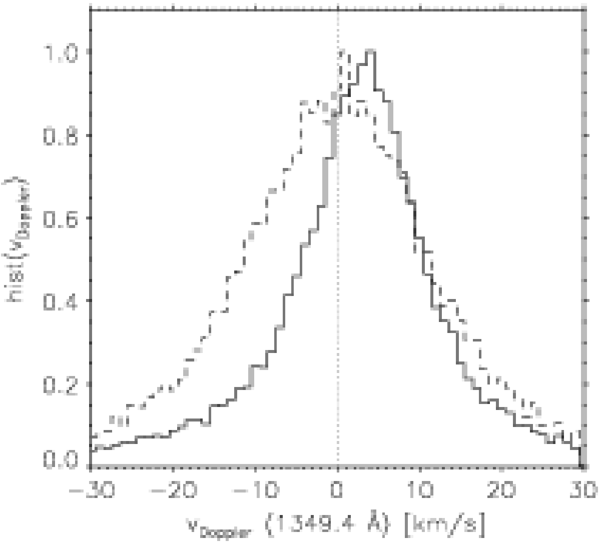


Redfield et al. (2003) . The Fe XIX 1118 Line was also detected in FUSE spectra.

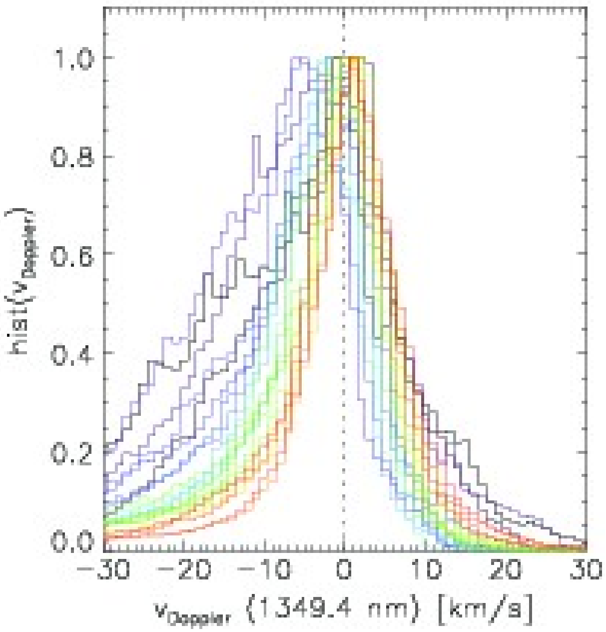


Ayres et al. (2003). Fe XII 1242, 1349 are also observed in many stellar spectra. Hot plasma with no blue shifts.

Solar spectra of the Fe XII 1349 A line (Testa et al. ApJ 827, 99 (2016)) and simulated Doppler shifts. Fe XII lines formed in low corona when weak heating (small blue shift) and near top of TR when strong heating (red shift).

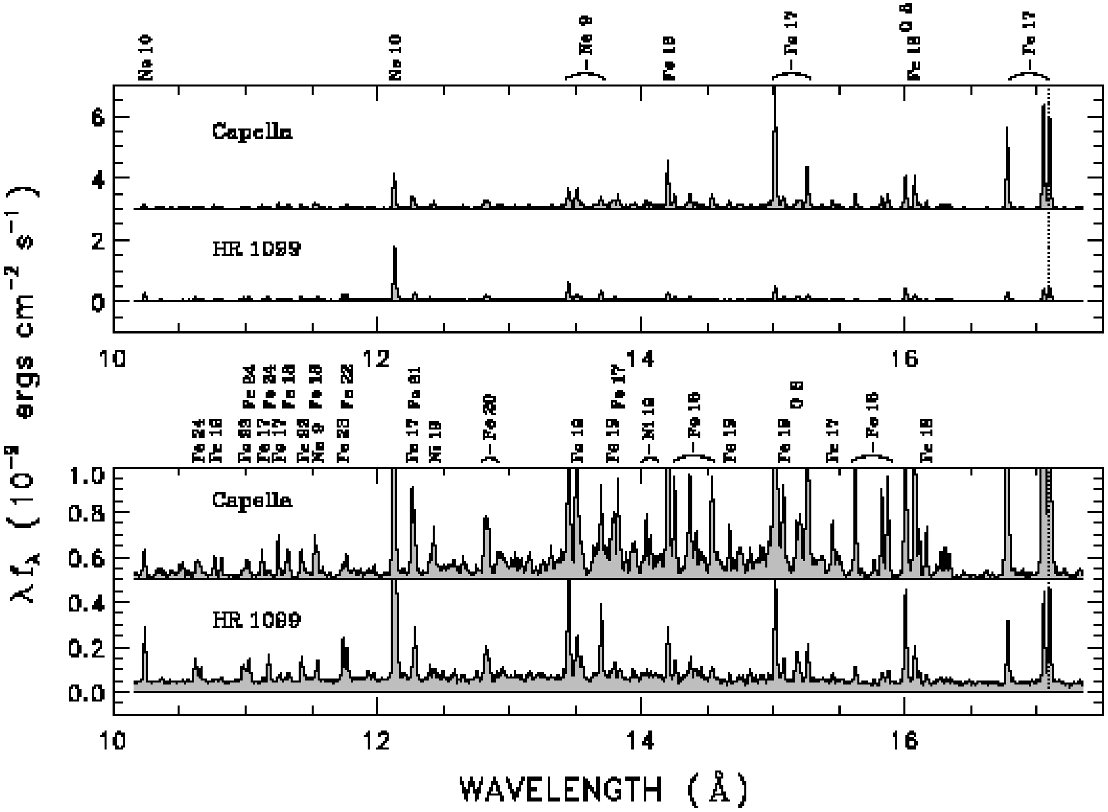


Doppler shift histograms obtained with IRIS for two different active regions.



Doppler shift histograms at different times during a Bifrost 3D MHD simulation. 30 km/s requires R=10,000.

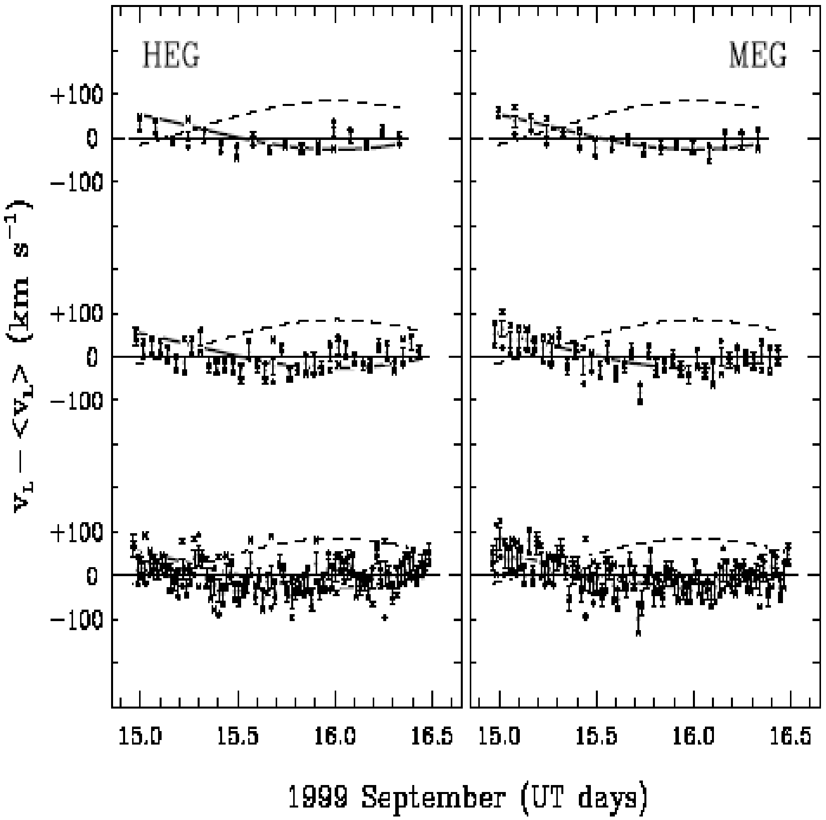
Chandra spectra of two very bright binaries



Note the complex spectrum.

Is it possible to measure stellar coronal gas velocities with current X-ray spectrometers?

- Doppler shifts of the Ne X 12.1Å line of HR 1099 with Chandra HEG (resolution ~300 km/s)
- Data binned at 30, 60, 120 s
- Thick solid line is predicted radial velocity of the K1 IV star. Thin line is for the G5 V star.
- Probably see changing radial velocity of the K1 IV star but no flows or flare Doppler shifts.
- Also no Doppler shifts seen for quiescent and flaring σ^2 CrB (Osten et al. ApJ 582, 1073 (2003))



Ayres et al. (ApJ 549, 554 (2001))

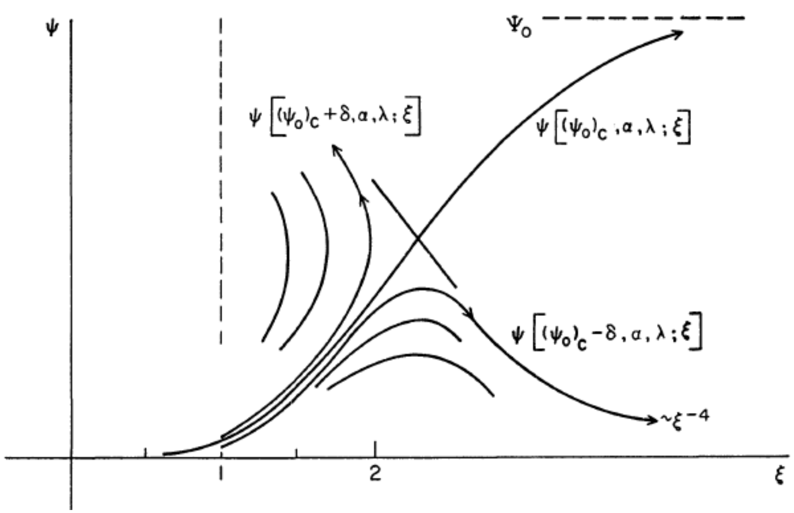
Conclusions

- Survival of an exoplanet's atmosphere depends mostly on gravity and to a lesser extent host star XUV flux.
- Proton events and CMEs can make the surface of an exoplanet with an atmosphere uninhabitable.
- Lynx can evaluate exoplanet habitability by (1) detecting CMEs and coronal plasma expansion, (2) estimating proton fluxes during impulsive flares on dMe stars, and (3) obtaining high S/N X-ray spectra with which to estimate EUV spectra.
- 30 km/s resolution (R=10,000) would measure coronal outflow speeds and separate blue-shifted velocity components in complex X-ray spectra.

Thank you for your attention

A very short primer on hydrodynamic winds driven by thermal and Alfven wave pressure (Parker-type winds)

- Fundamental paper is Parker (ApJ 132, 821 (1960)).
- Solve the hydrodynamic equations in a gravitational field with 2 boundary conditions v(0)small and P(∞)=0.
- Only solution requires that the flow pass through a critical point $v_{crit}=v_{esc}(r)$ where $\xi\varphi=GM_{sun}M_H/4ckT_0$
- Similar solutions for Alfven wave force wind.



$\xi=r/c$ r=radial distance c=scalelength

$\Phi=m_Hv^2/2kT$=kinetic/thermal energy

For Sun, $v_{esc}\approx600$ km/s (surface) and

$v_\infty=400$ (slow wind) to 800 (fast) km/s