Minicourse on Stellar Activity V: Host Star Radiation

Jeffrey Linsky

JILA/University of Colorado

Boulder Colorado USA

Department of Astronomy

Yale University

January 27, 2016

http://

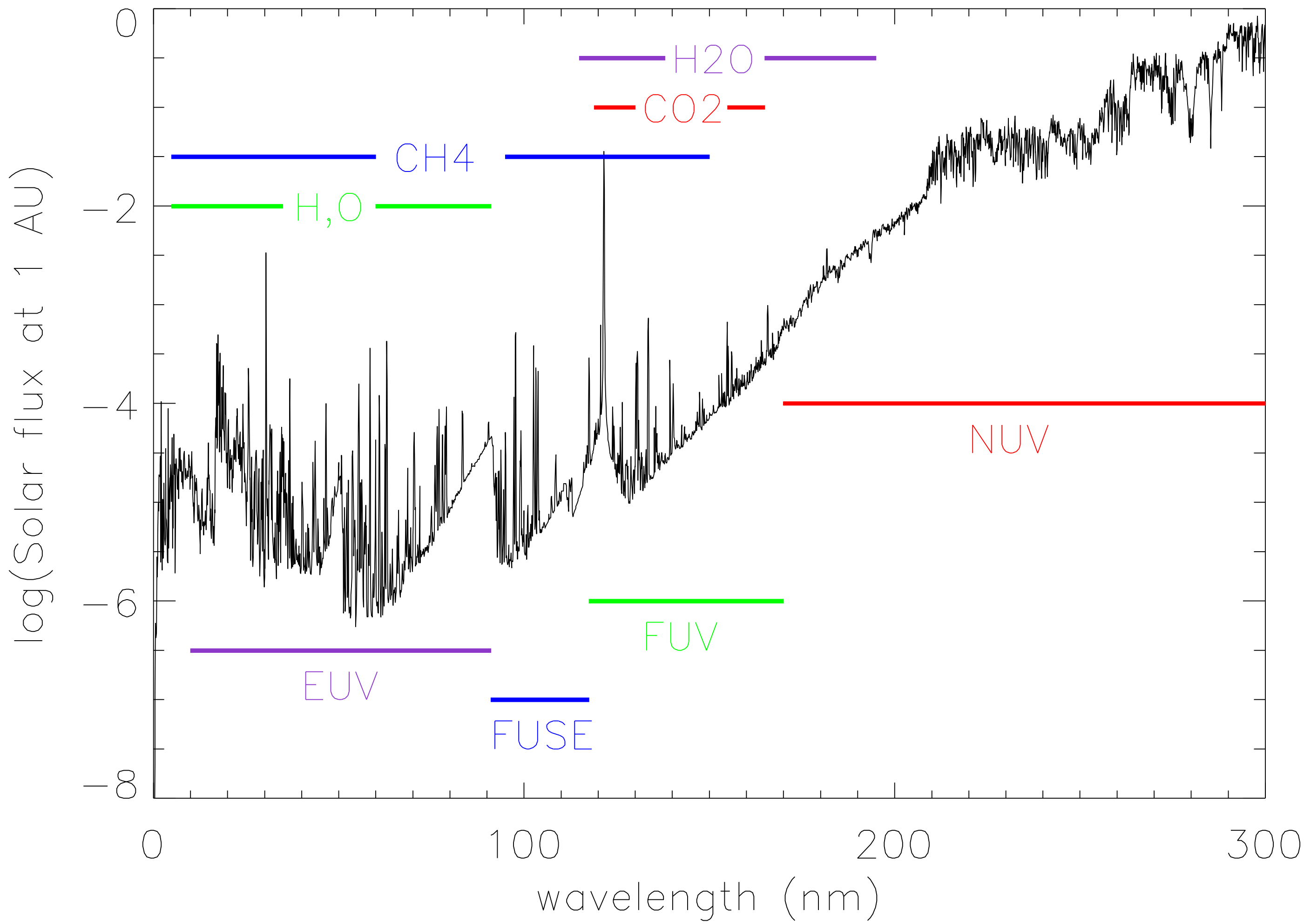
Suggested reading

- Murray-Clay et al. “Atmospheric escape from hot Jupiters” ApJ 693, 23 (2009).
- Fontenla et al. “Solar spectral irradiance, solar activity, and the near-ultraviolet”, ApJ 809, 157 (2015).
- France et al. “The UV radiation environment of M dwarf exoplanet host stars”, ApJ 763, 149 (2013).
- Linsky, France, & Ayres “Computing intrinsic Lyα fluxes of F5 to M5 stars”, ApJ 766, 69 (2013).
- Linsky, Fontenla, & France “The intrinsic extreme-UV fluxes of F5 V to M5 V stars” ApJ 780, 61 (2-014).
- Wood et al. “Solar Lyα emission lines in the Hubble Space Telescope archive: Intrinsic fluxes and absorption from the heliosphere and astrospheres”, ApJS 159, 118 (2005).
- Tian et al. “High stellar FUV/NUV ratio and oxygen contents in the atmospheres of potentially habitable planets”, Earth and Planetary Science letters 385, 22 (2014).

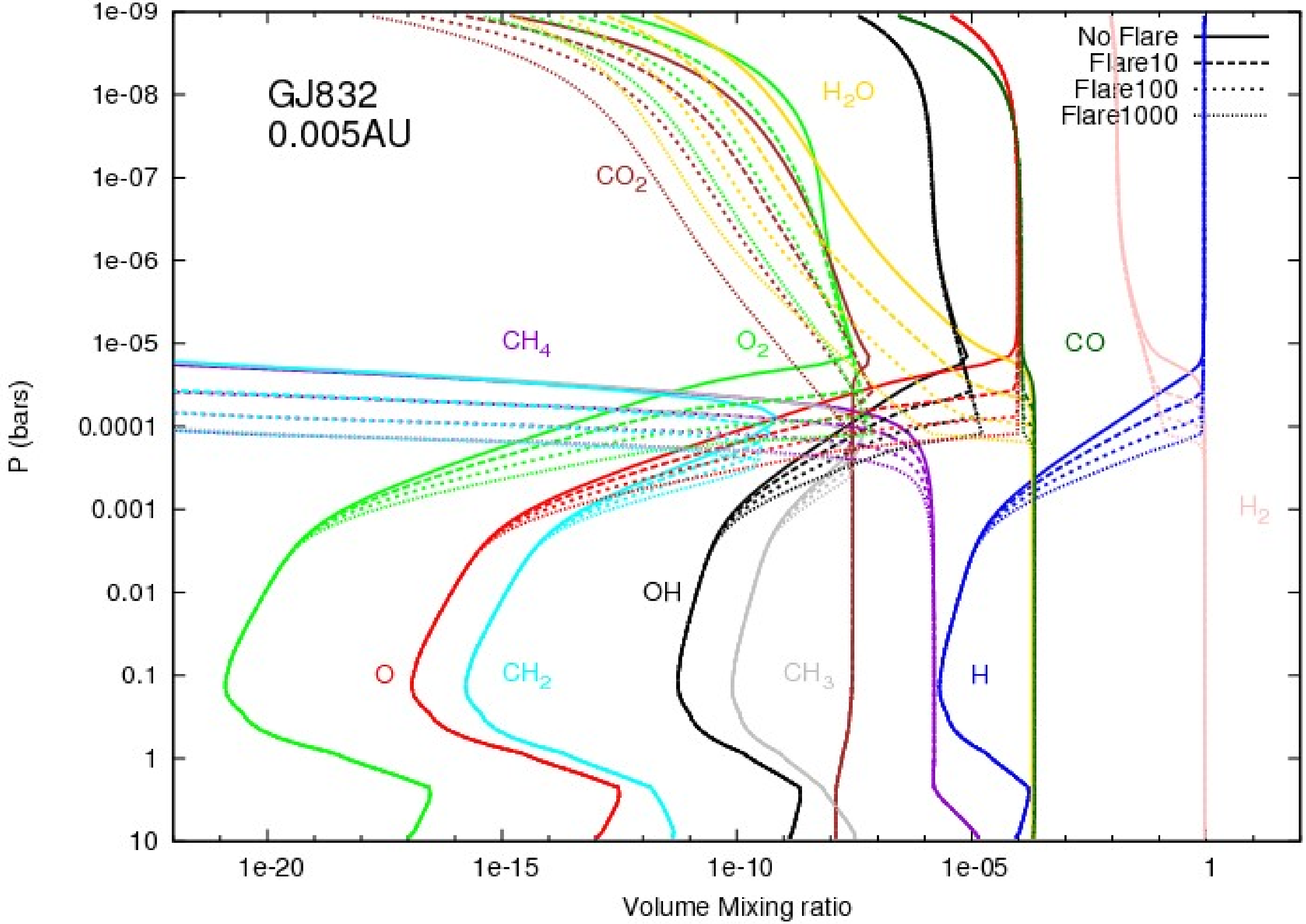
Topics to be covered

- Why the UV, EUV, and X-ray spectra of host stars are important (e.g., photochemistry and mass loss).
- Comparison of the solar and M dwarf UV spectra.
- Reconstructing the host star's Lyman-α flux.
- Estimating the host star's EUV flux.

Photodissociation and Photoionization Cross Sections of some Important Molecules in Exoplanet Atmospheres



Photochemistry of an M dwarf atmosphere as function of host star UV flux (Miguel et al. MNRAS 446, 345 (2015))

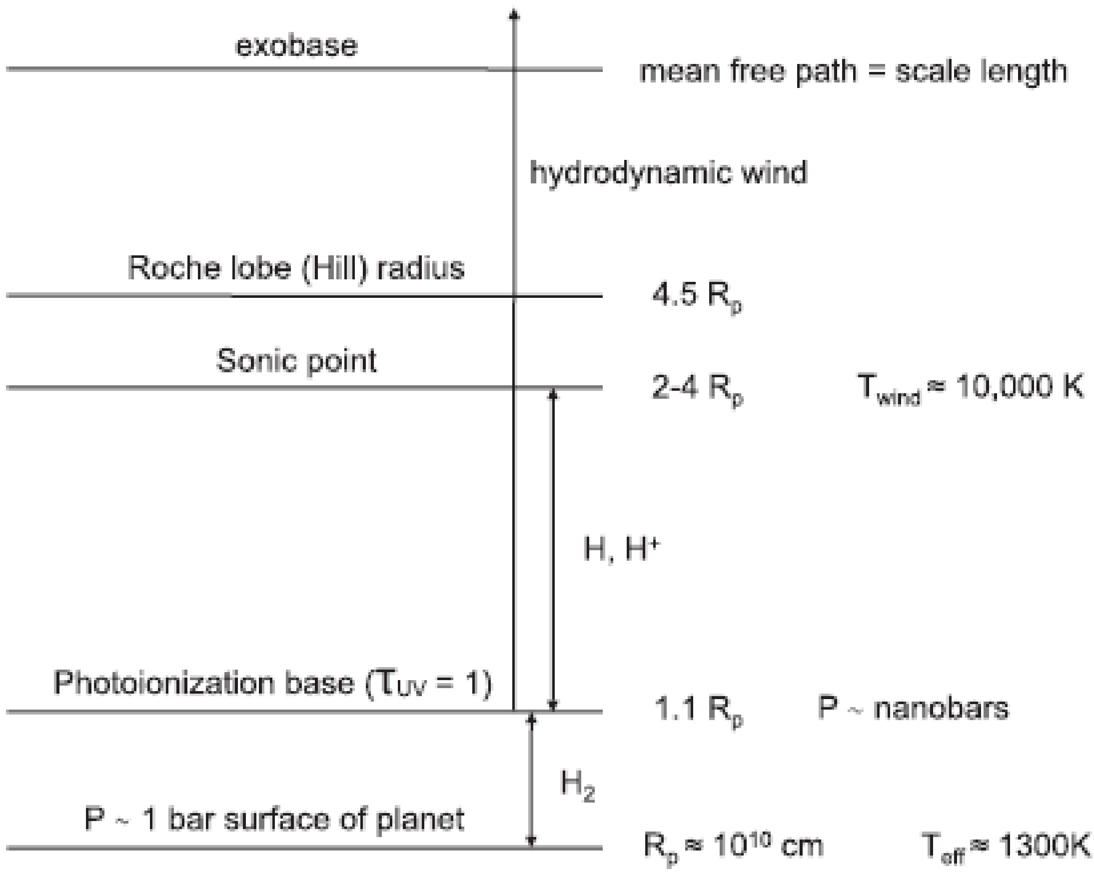


Physical processes controlling the mass loss from a planetary atmosphere close to its host star

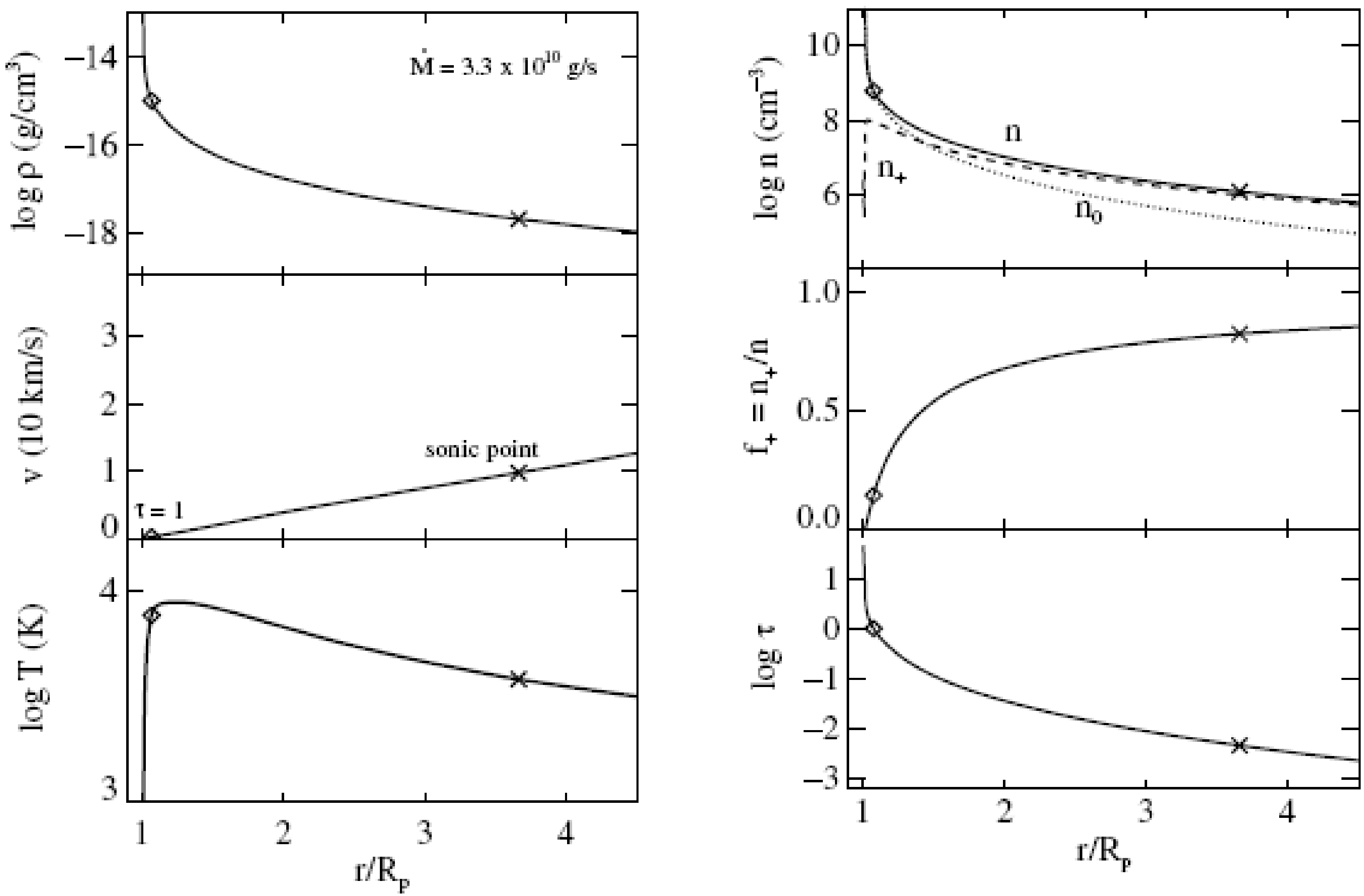
- Hydrodynamic outflow (gas collisional up to the sonic point) driven by EUV radiation from the host star.
- EUV photons photo-ionize hydrogen and heat the outer atmosphere leading to pick-up by the stellar wind magnetic field.
- Atmosphere inflates to a region of lower gravity and thermal pressure forces mass loss through the sonic point (Parker type transonic wind but heated from the outside).
- Stellar gravity can enhance exoplanet mass loss through Roche lobe overflow.
- Stellar winds can remove ions and neutrals above the planet's magnetosphere.

Atmosphere and exosphere model of HD 209458b

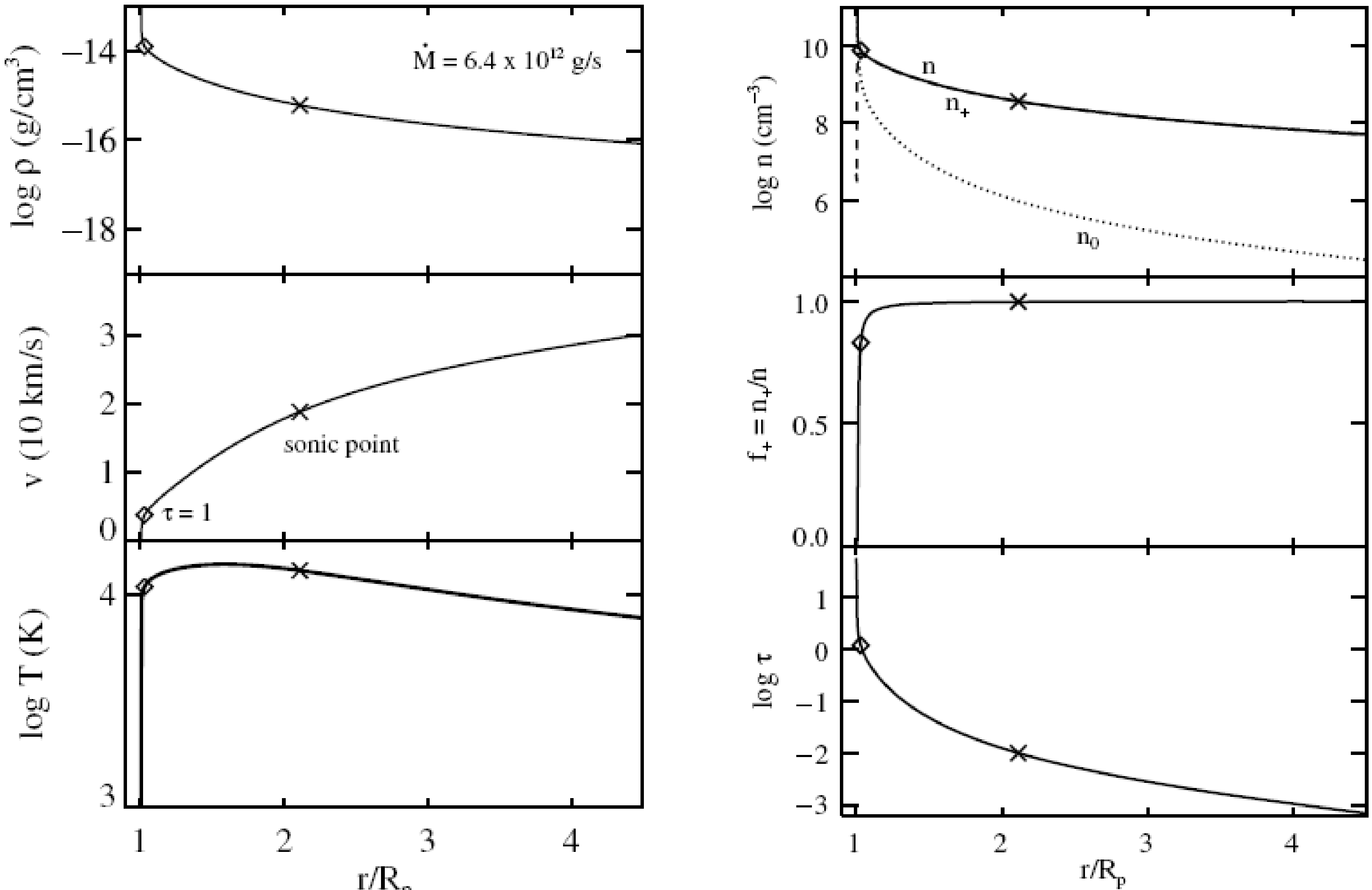
(Murray-Clay et al. ApJ 693, 23 (2009))



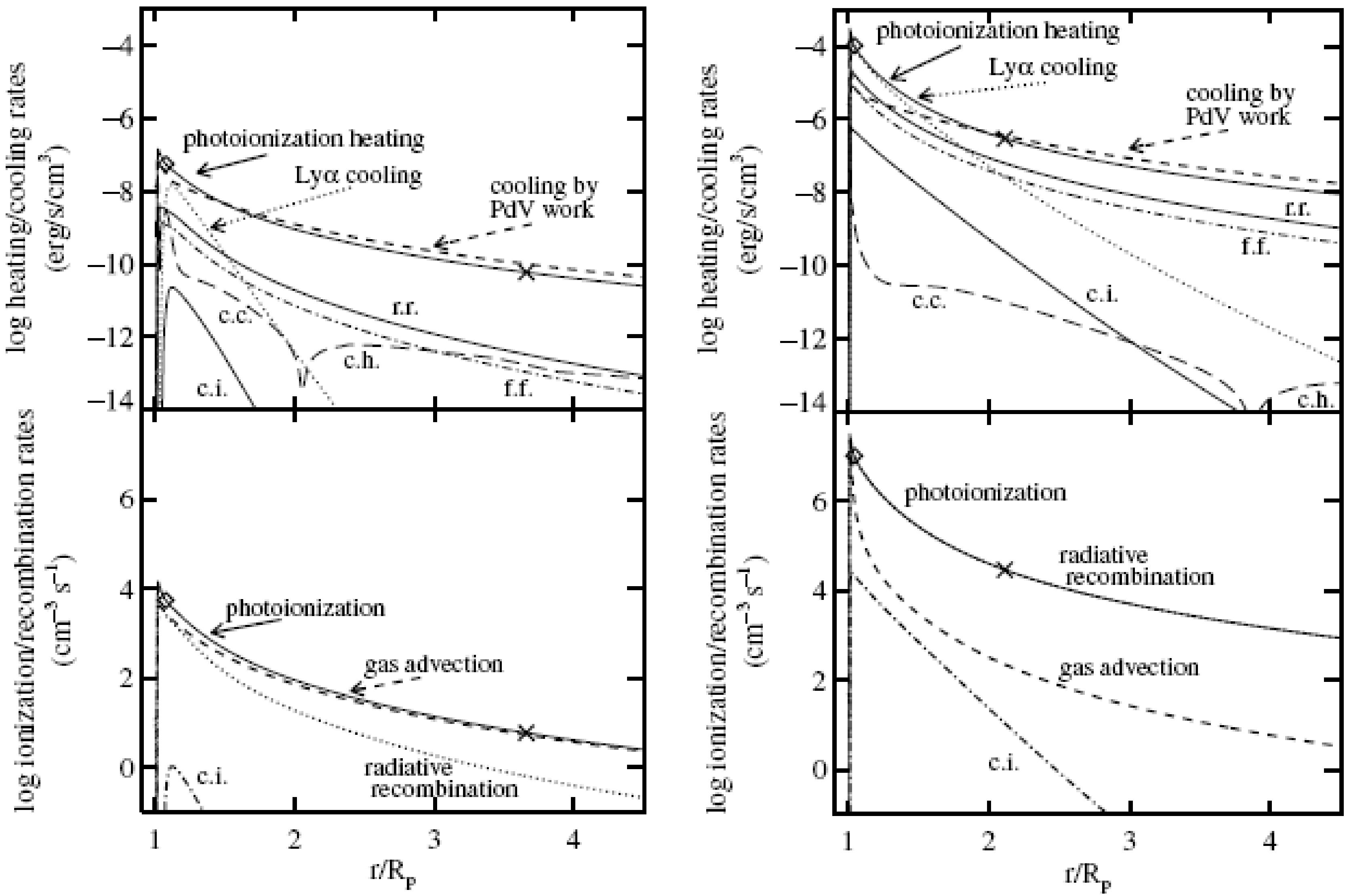
Wind model for HD 209458b (0.7 M_J planet at 0.05 AU from a G2 V star with f(EUV)=450 ergs/cm^2/s



Wind model for HD 209458b assuming f(EUV)=500,000 erg/cm²/s (1000 times larger)

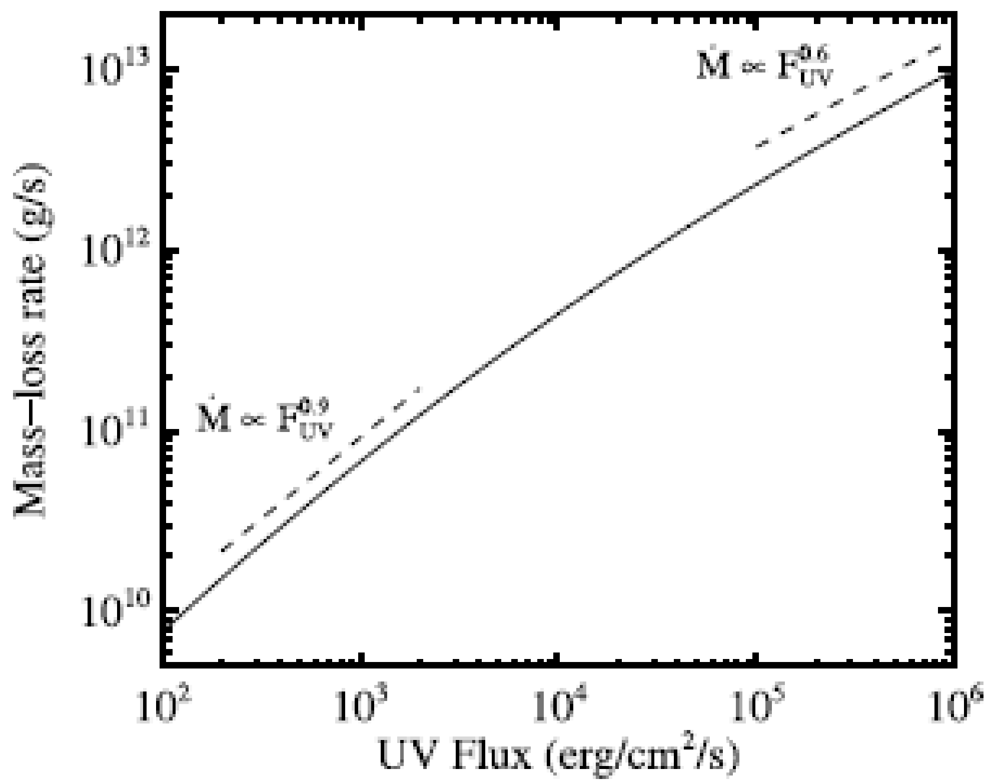


Heating/cooling/ionization for HD209458b model with f(EUV)=450 (left) and 500,000 (right)

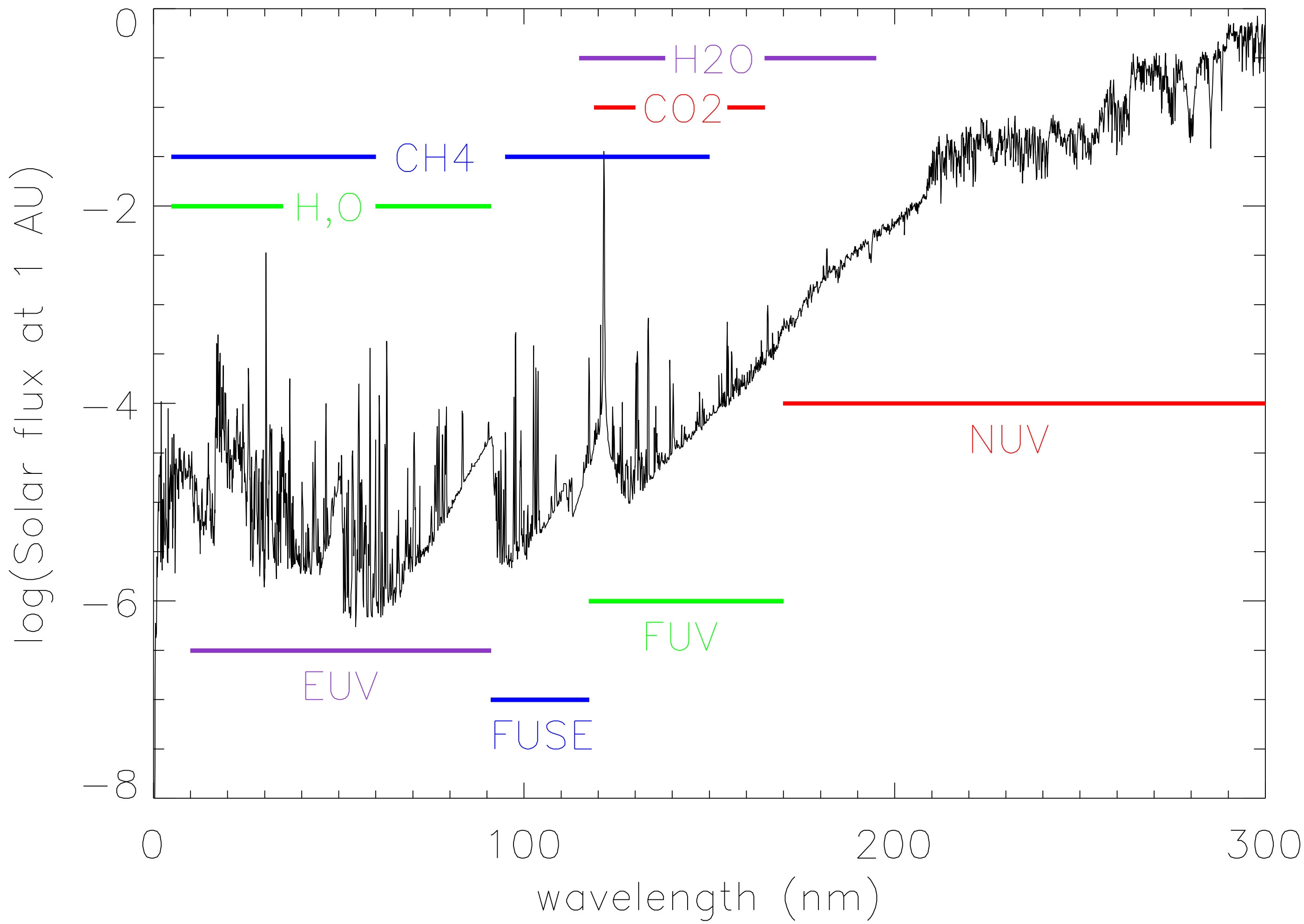


Mass-loss rate for HD 209458b model as a function of f(EUV)

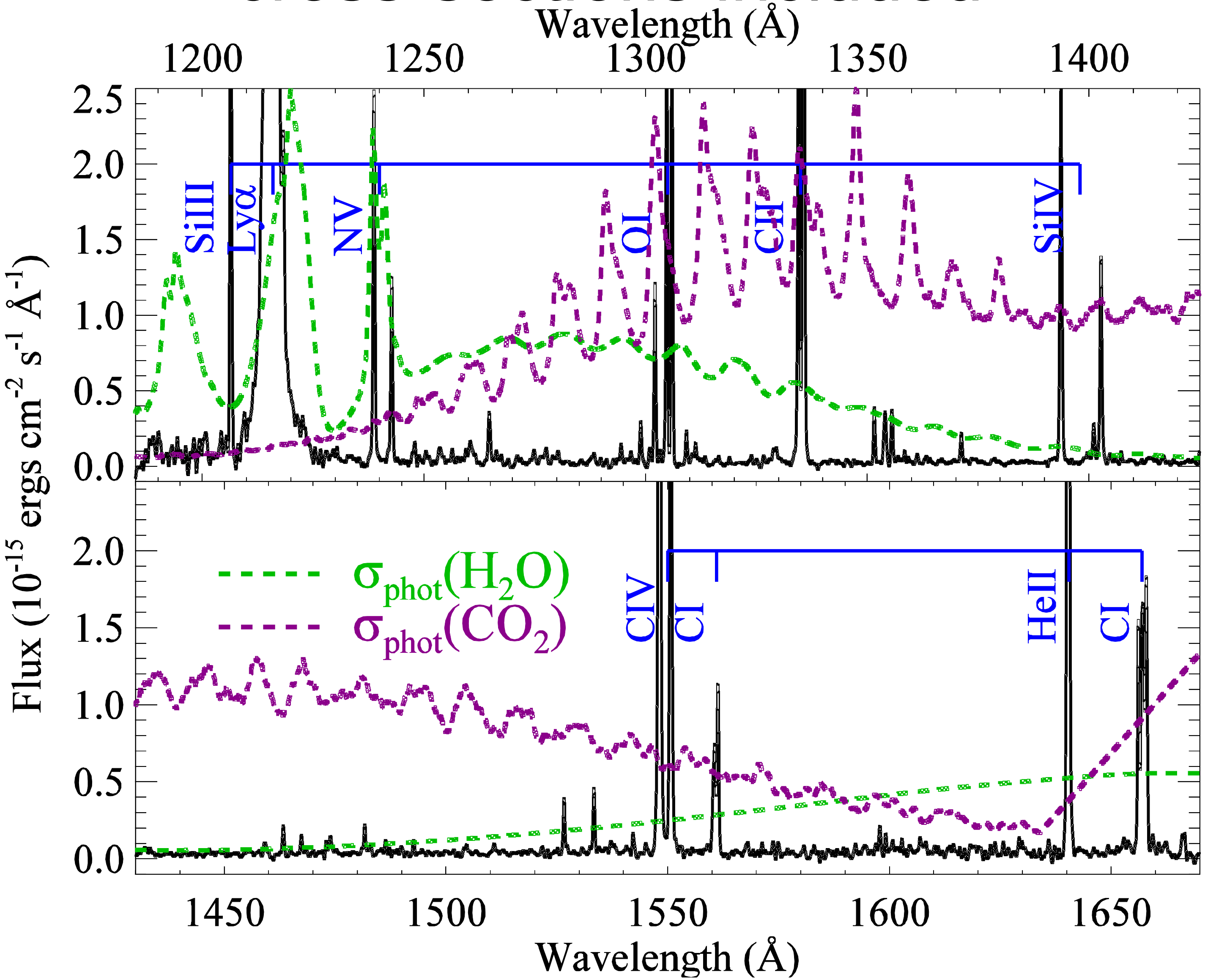
- Solar EUV flux (13.6-40 eV) at 0.05 AU is 450 ergs/cm^2/s.
- Predicts $\dot{M}$=3.3x10^{10} g/s.
- M_{pl}=1.2x10^{30} g.
- $\dot{M}/M_{pl}$=8x10^{-13} yr.
- During T Tauri phase, HD 209458b would have lost 0.1% of its mass in 10^7 yr.



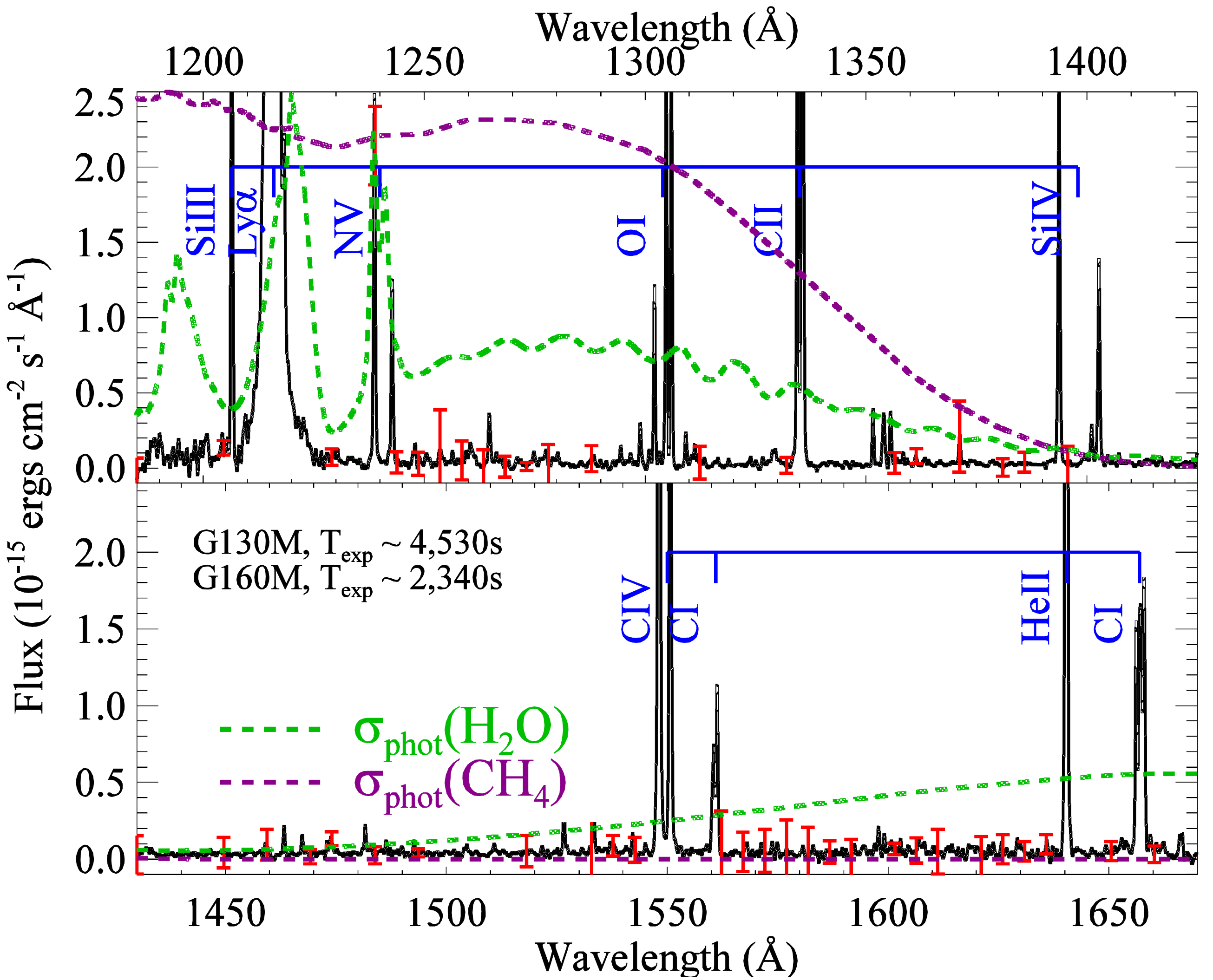
Photodissociation and Photoionization Cross Sections of some Important Molecules in Exoplanet Atmospheres



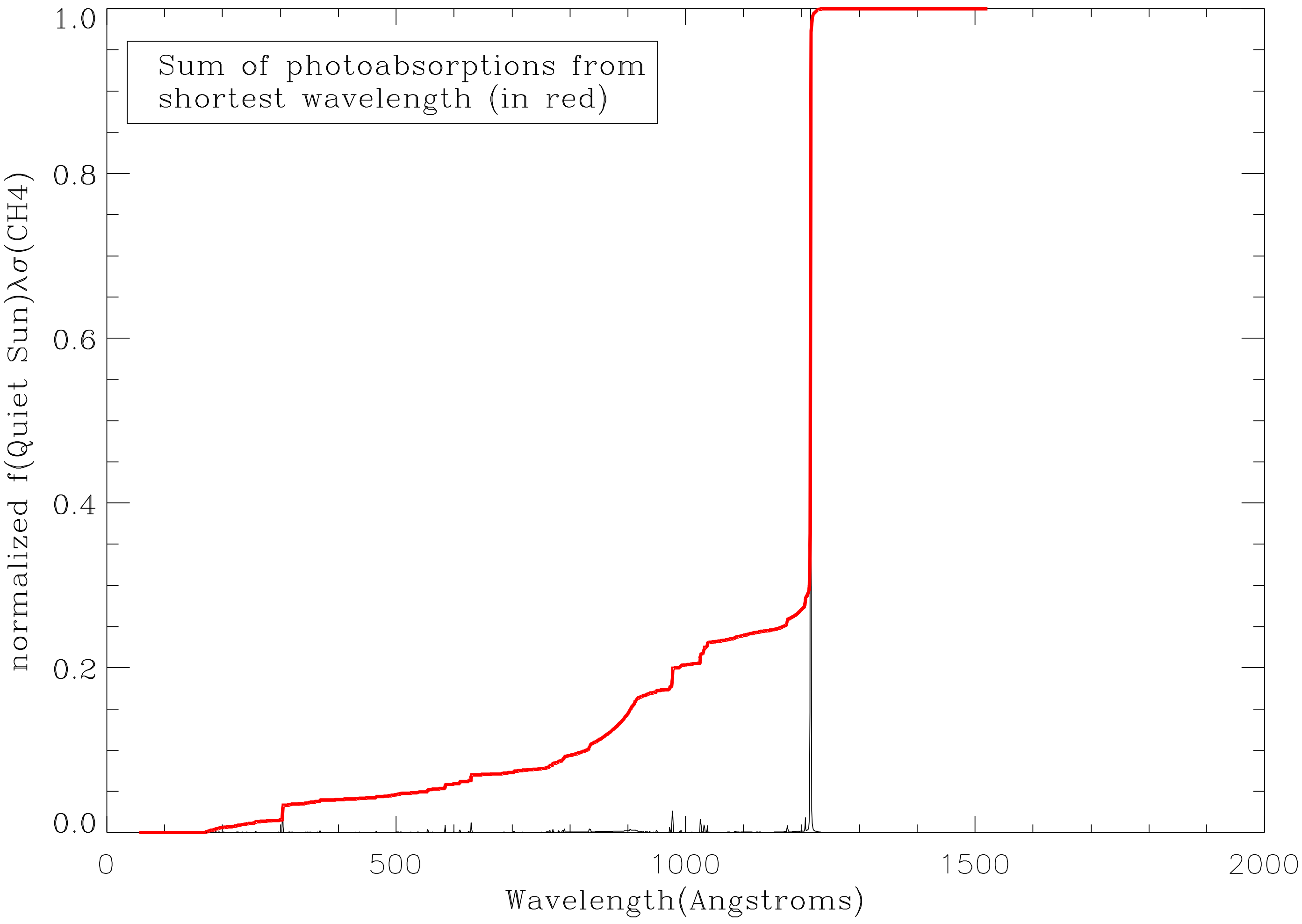
UV spectrum of GJ832 with H_2O and CO_2 cross-sections included



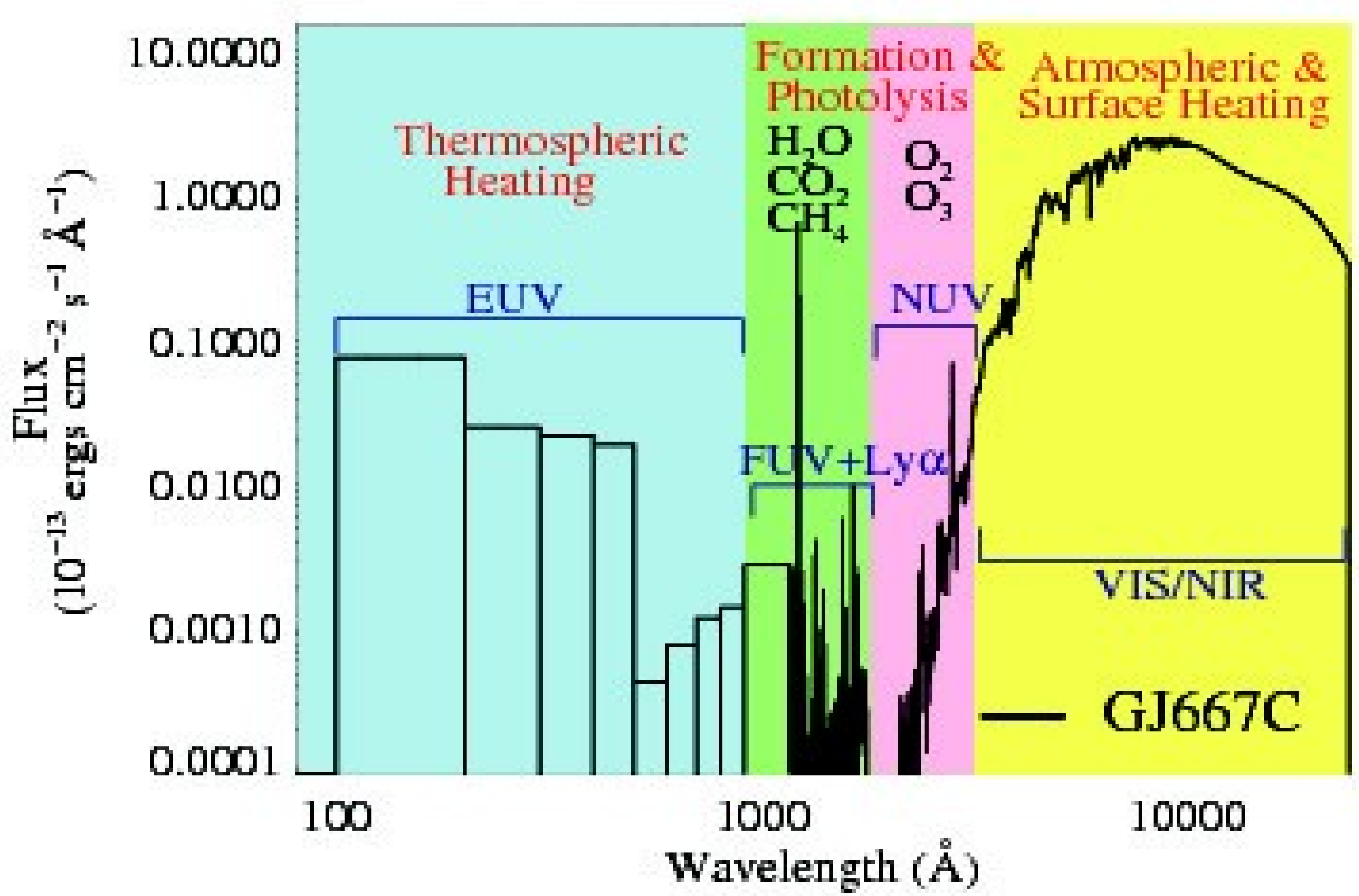
Simulated spectrum of GJ 436 (M2.5 V with a $0.073M_J$ exoplanet). Note emission lines and photo-absorption cross-sections of H_2O and CH_4



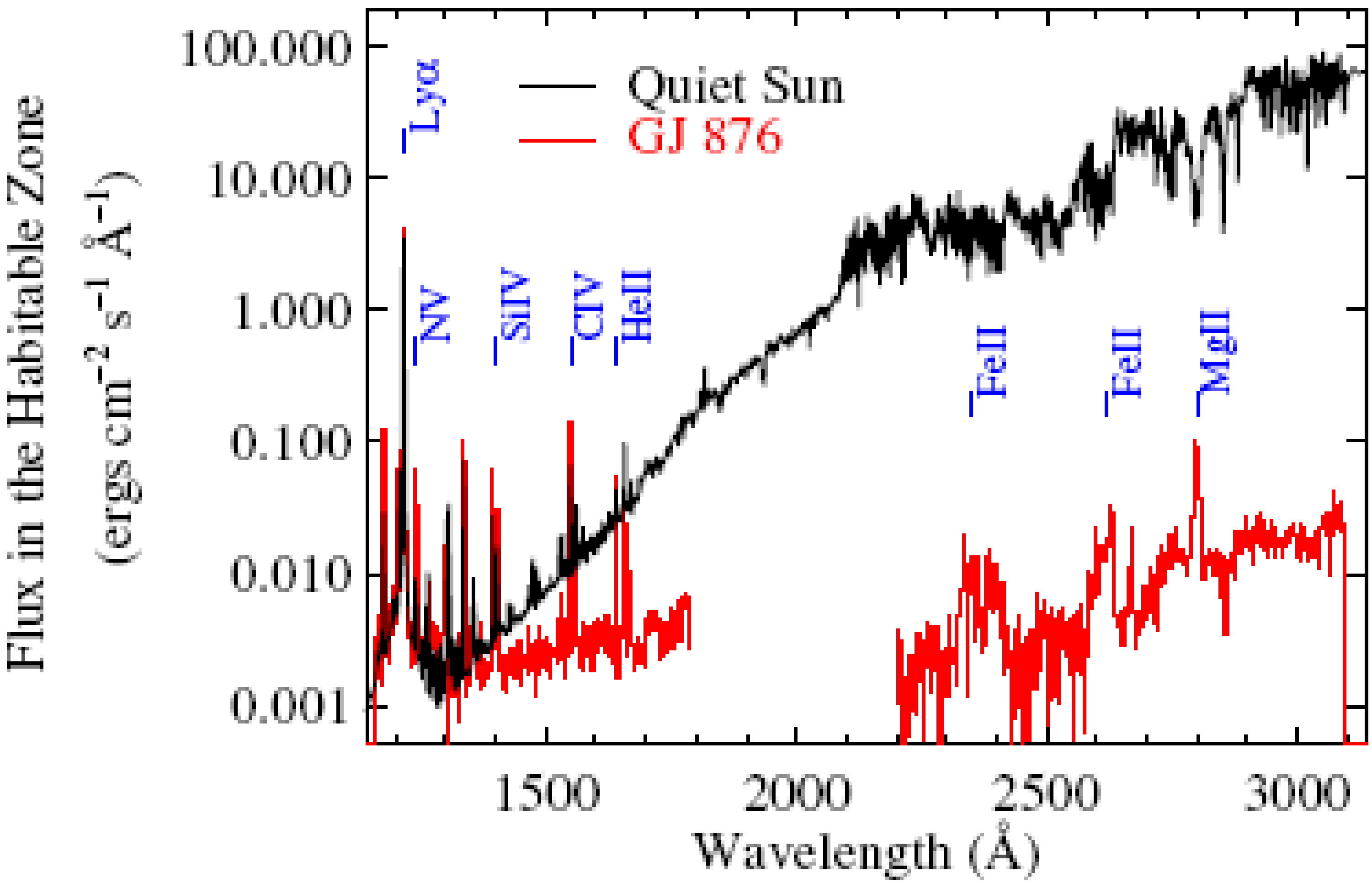
Summation of the Photoabsorption of CH_4 by the Quiet Sun Spectrum



Spectral energy distribution for GJ667C (M1.5 V, 6.9 pc) from HST MUSCLES Treasury Survey (France et al. 2016)



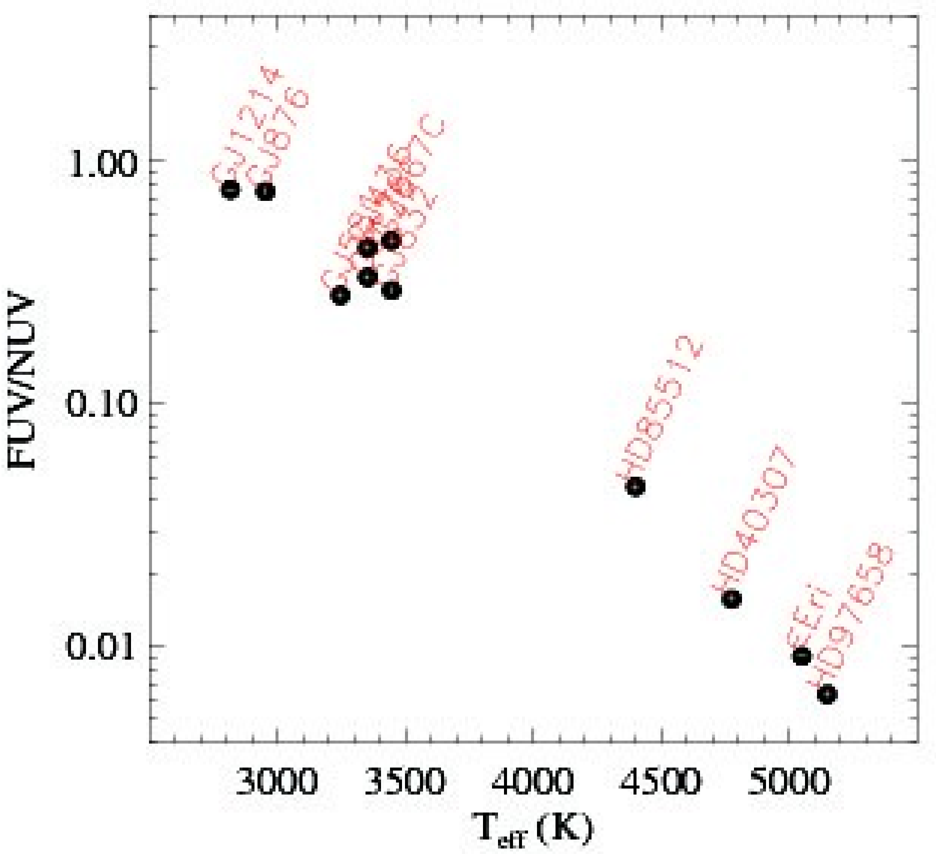
Comparison of FUV and NUV fluxes of GJ 876 (M4 V) observed by COS with the Quiet Sun (France et al. 2012)



Comparing Sun at 1 AU to GJ 876 at 0.21 AU.

FUV/NUV flux ratio for M and K stars (MUSCLES Treasury Survey)

- Coordinated HST, X-ray, optical (France et al. 2016).
- FUV (912-1700 Å)
- NUV (1700-3200 Å
- FUV/NUV ratio decreases a factor of 100 from M6 V to K1 V and a factor of 1000 from M6 V to the Sun.
- High FUV/NUV produces a high concentration of O (from photolysis of H2O and CO2) but little photo-dissociation of O2 and O3. An abiotic path to an oxygen rich atmosphere.



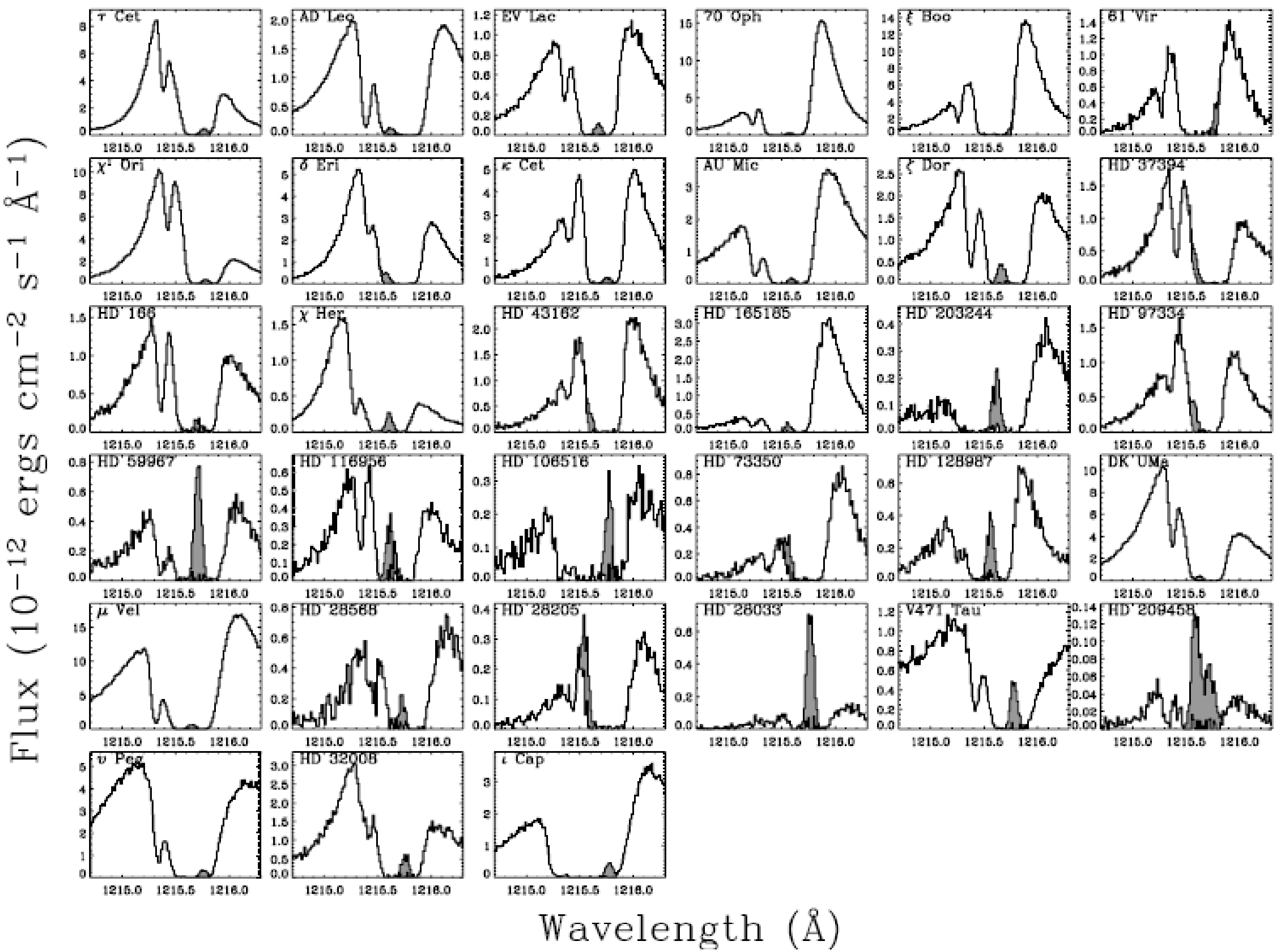
See Tian et al. EPSL 385, 22 (2014) and Domagal-Goldman et al. ApJ 792, 90 (2014)

Fluxes in the habitable zones of GJ876 (0.21 AU) and the Sun (1.0 AU) (France et al. 2012)

Table 1
Habitable Zone UV Fluxes

	$\Delta\lambda$[a] (Å)	Solar[b] (erg cm^{-2} s^{-1})	GJ876[c] (erg cm^{-2} s^{-1})
F(Lyα)[d]	(1210–1220)	5.6×10^{0}	$9.5\ (\pm\ 0.7) \times 10^{0}$
F(N v)[e]	(1235–1245)	1.8×10^{-2}	$2.0\ (\pm\ 0.1) \times 10^{-1}$
F(Si IV)[e]	(1390–1410)	5.6×10^{-2}	$1.9\ (\pm\ 0.1) \times 10^{-1}$
F(C IV)	(1545–1555)	1.2×10^{-1}	$4.2\ (\pm\ 0.3) \times 10^{-1}$
F(He II)	(1635–1645)	2.4×10^{-2}	$1.2\ (\pm\ 0.1) \times 10^{-1}$
F(FUV)	(1150–1210) + (1220–1790)	1.8×10^{1}	$4.1\ (\pm\ 0.6) \times 10^{0}$
F(NUV)	(2200–3140)	2.2×10^{4}	$9.8\ (\pm\ 0.6) \times 10^{0}$
F(Lyα)/F(FUV)		0.3	2.3
F(Lyα)/F(FUV+NUV)		2.6×10^{-4}	0.7

A Rogue's Gallery of Deformed Stellar Lyman-α Emission Lines (Wood et al. 2005)



Five techniques for reconstructing the intrinsic Lyman-α flux

(1) Use the shape of the D I Lyman-α and ISM absorption in metal lines to infer the flux removed from the H I Lyman-α line. Wood et al. (2005) reconstructed the intrinsic Lyman-α flux for 40 dwarf stars. [Limited to log N(H I)<18.7 or d<40 pc.]

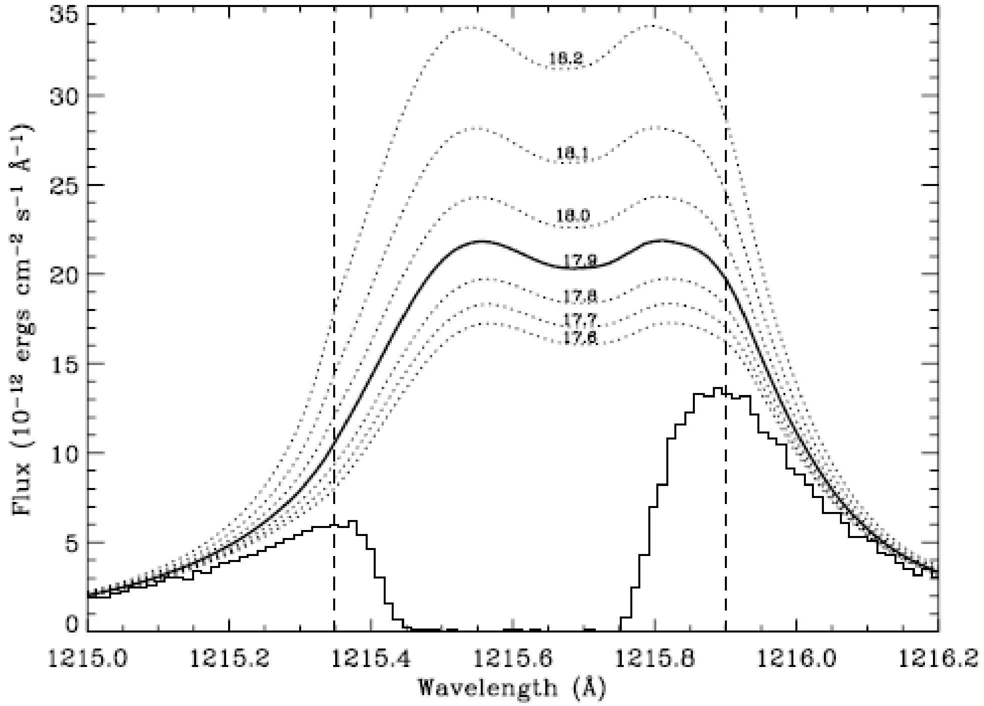
(2) X^2 minimization of assumed Gaussian Lyman-α shape and ISM absorption for 5 M dwarfs (France et al. 2011, 2013). [Limited to lines of sight with simple ISM velocity structure.]

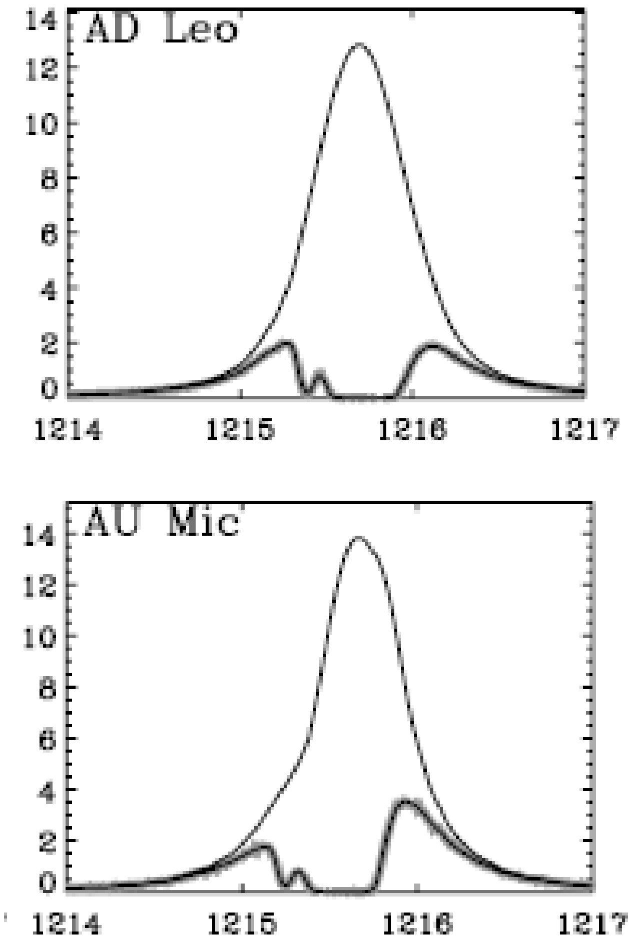
(3) Use fits to f(Lyman-α) vs. T_{eff} when know the stellar rotation period or another activity parameter.

(4) Scale from observed flux in emission lines formed at similar temperatures in the same or similar stellar chromospheres. New approach presented here.

(5) Observe high radial velocity stars.

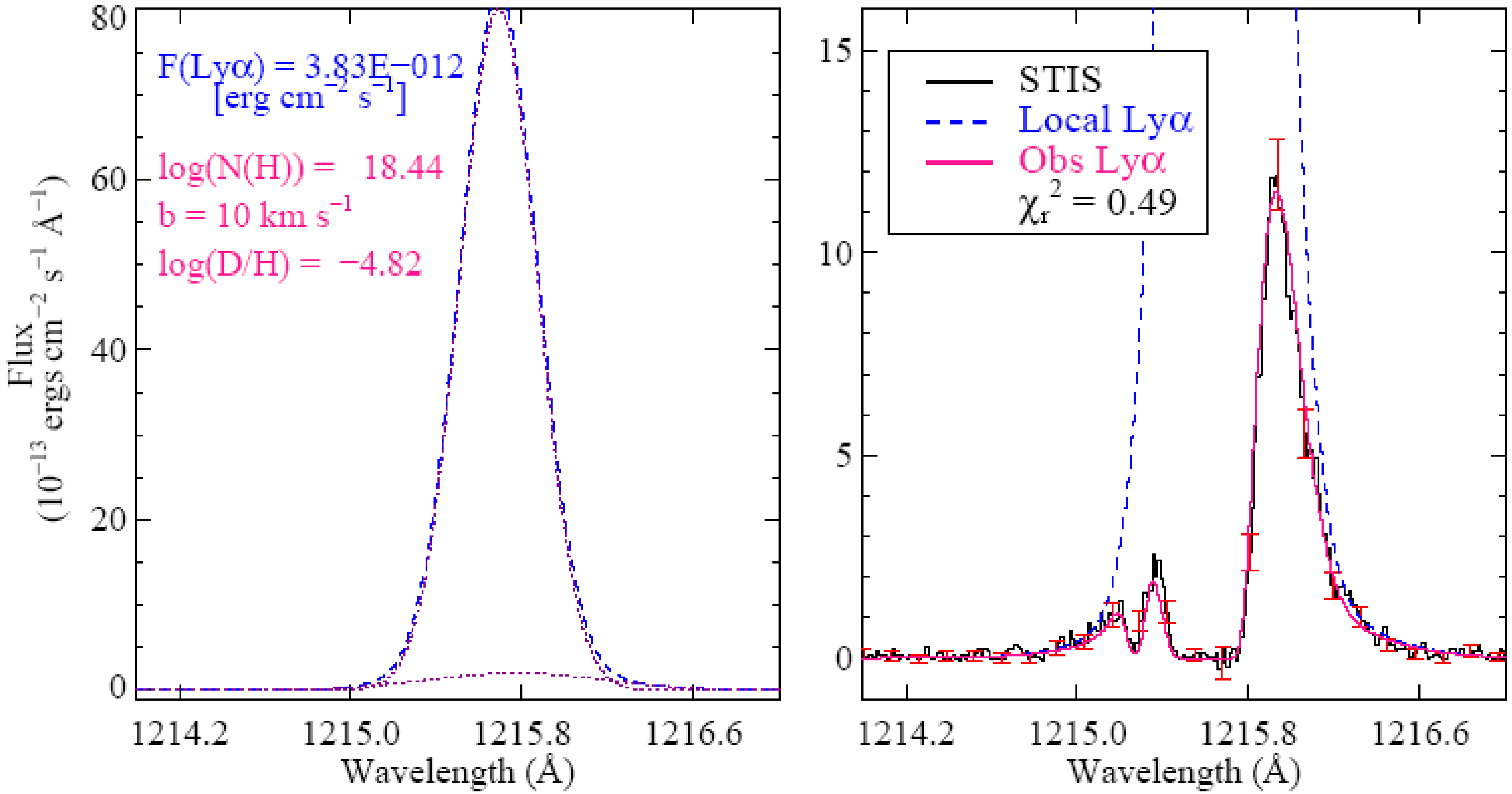
Reconstructing Lyman-α Line Profiles Using Information on the Local ISM (Wood et al. ApJS 159, 118 (2005).





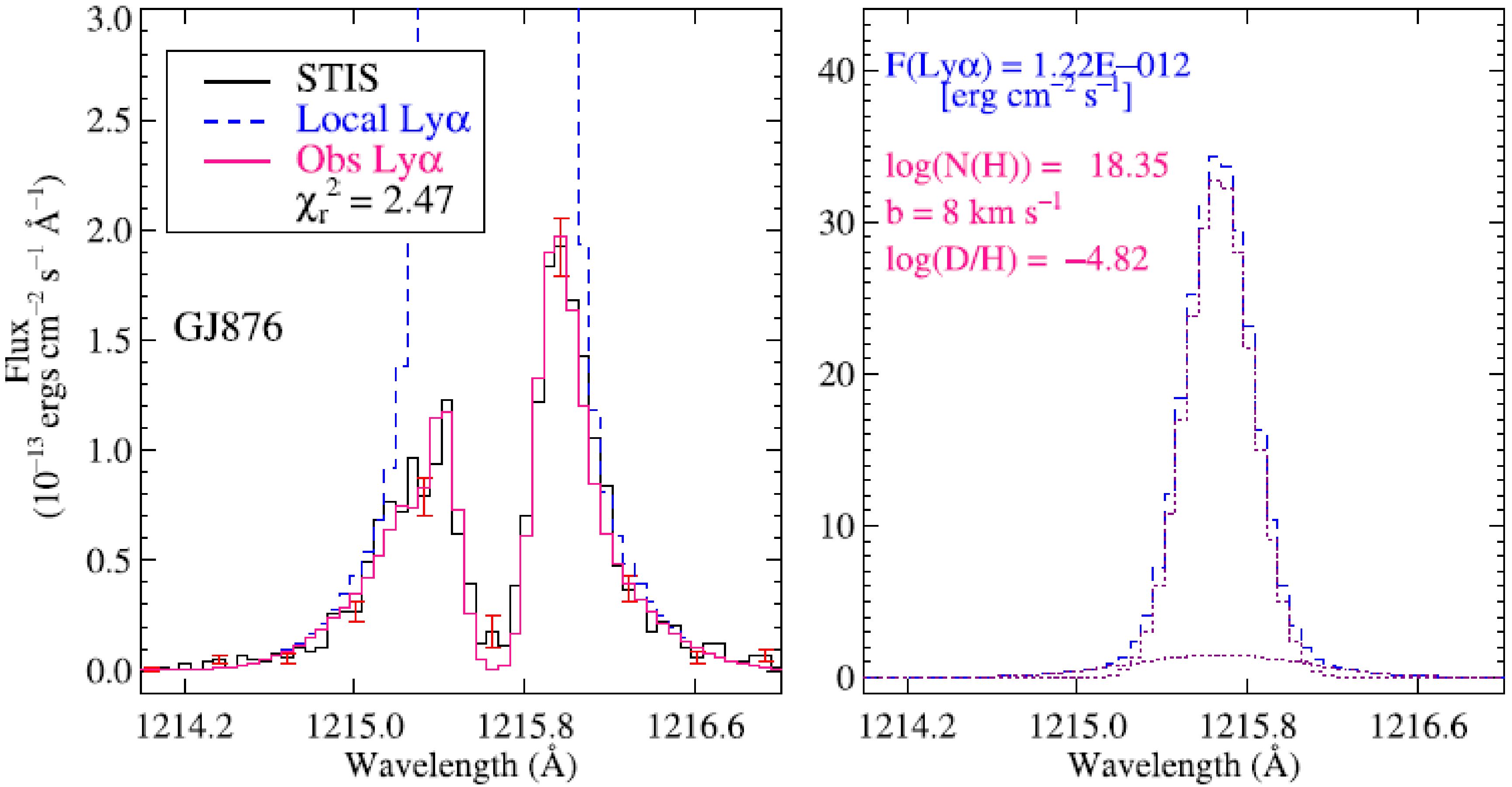
Left: ξ Boo A (G8 V). Right: AD Leo (M3.5 V) and AU Mic (M0 V).

Observed and reconstructed Lyman-α flux for GJ832 (M1.5V)



1 exoplanet at 3.4 AU.

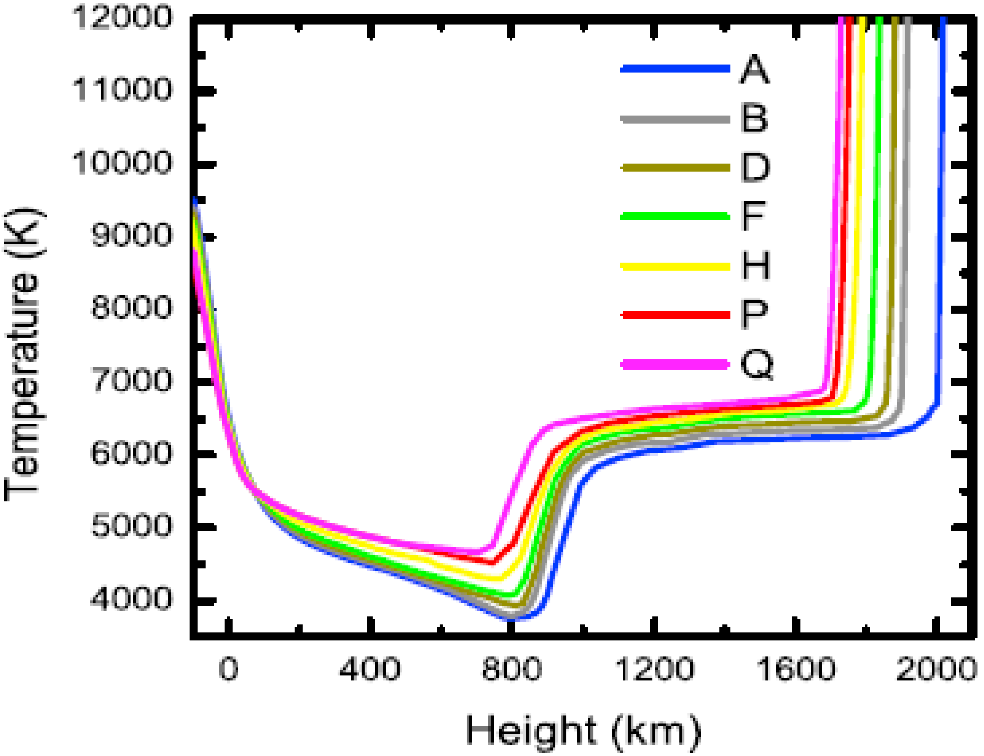
Observed and reconstructed Lyman-α flux for GJ876 (M5.0V)



4 exoplanets at 0.0208, 0.1296, 0.2083, and 0.3343 AU.

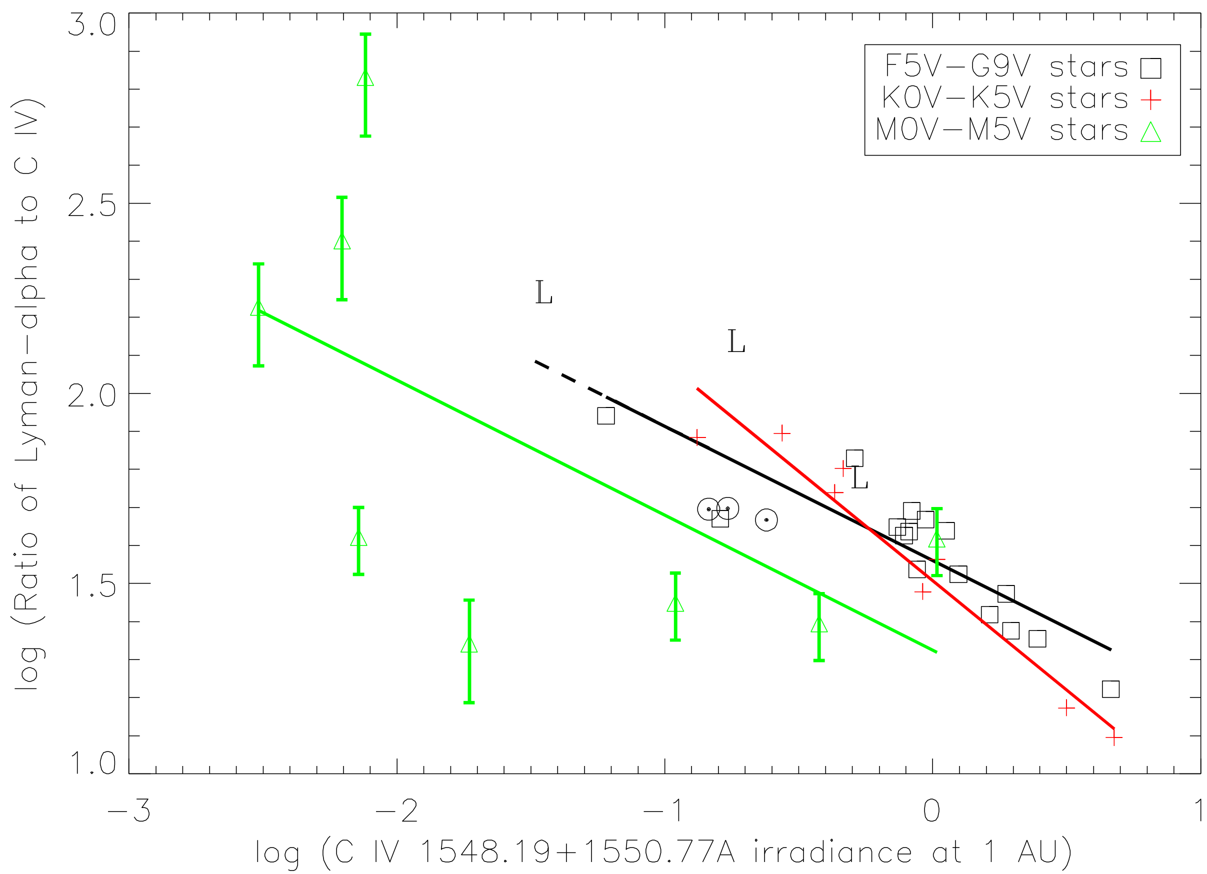
Semi-empirical chromosphere models for regions of the Sun with dark to bright UV emission which is a proxy for the heating rate (Fontenla et al. 2009)

- Model A fits the spectrum from a region of weak emission (low heating rate).
- Model Q fits the spectrum from a region of strongest emission (high heating rate).
- Note similar shapes!



Working hypothesis is that ratios of emission lines should depend weakly on emission line fluxes.

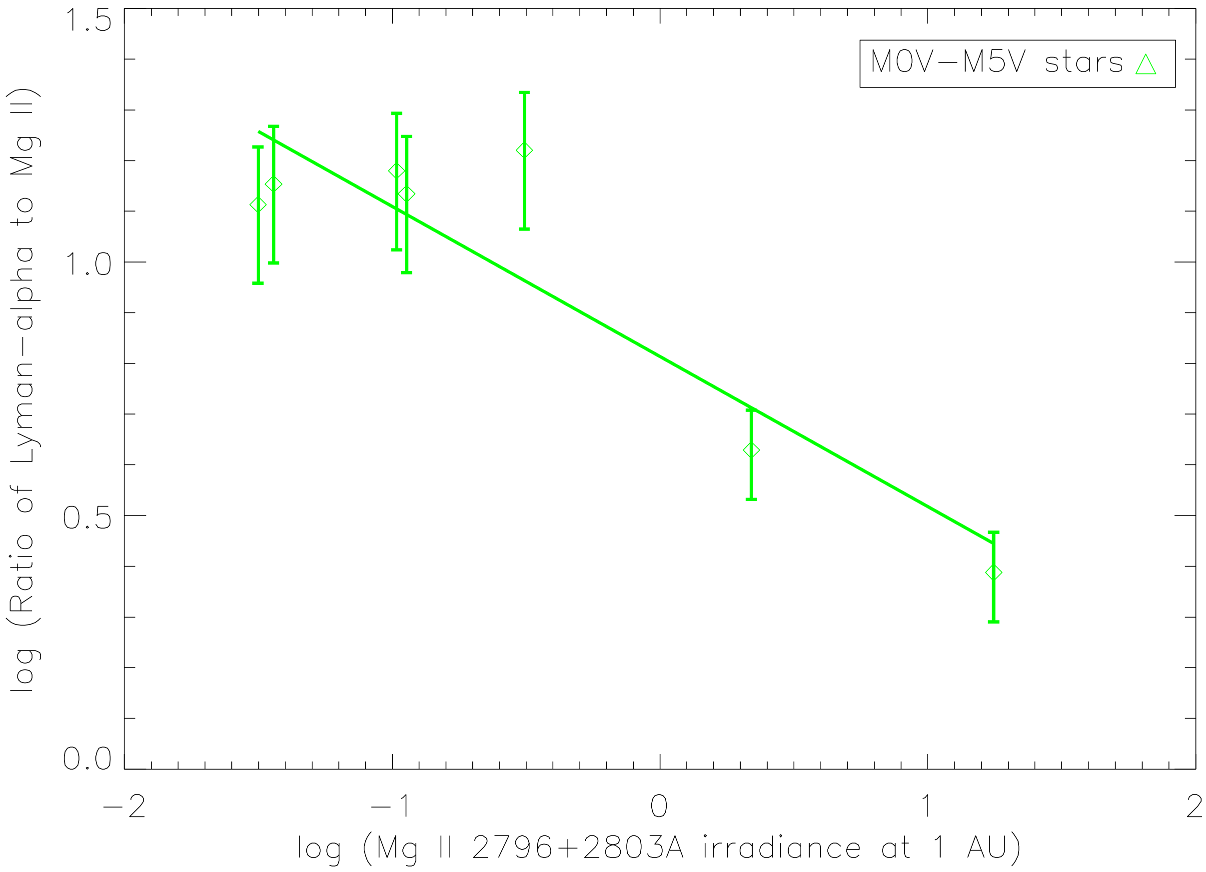
The reconstructed Lyman-α/C IV flux ratio depends smoothly on the observed C IV flux and spectral type (Linsky et al. ApJ 766, 69 (2013))



C IV formed near 60,000 K and Lyman-α formed near 10,000 K.

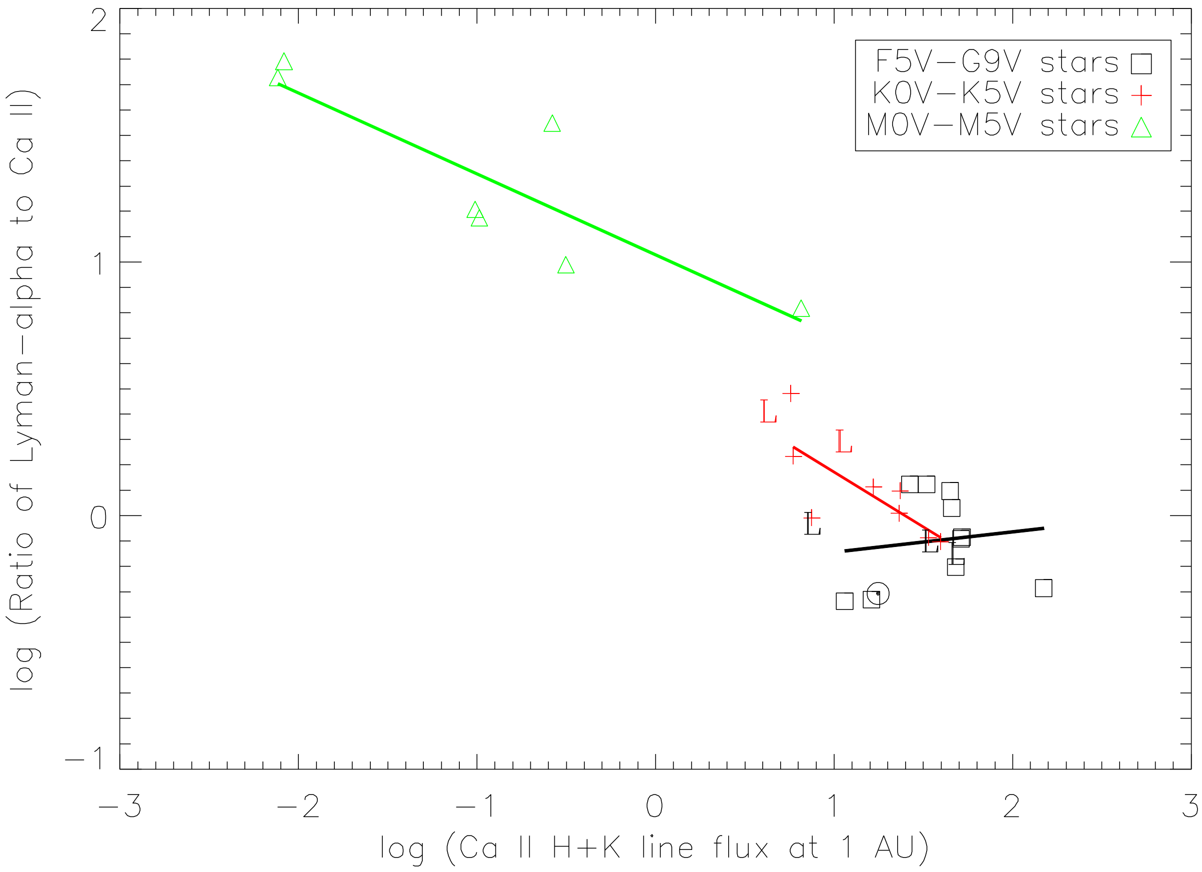
f(Lyman-α)/f(C IV)=A+B*f(C IV)

The reconstructed Lyman-α/Mg II flux ratio for M dwarf stars (note strong slope)

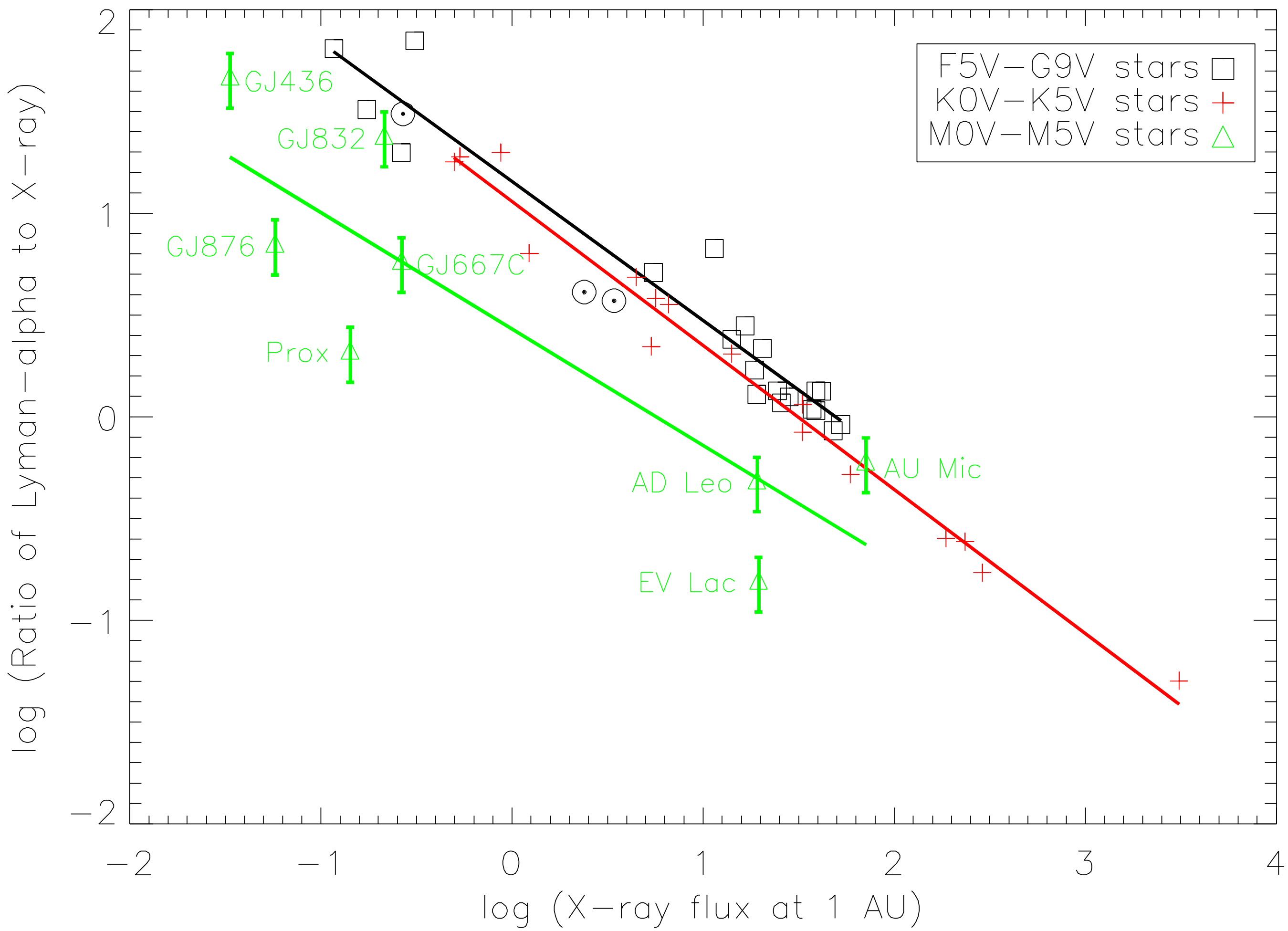


Mg II formed near 5,000 K and Lyman-α formed near 10,000 K. Both lines very optically thick.

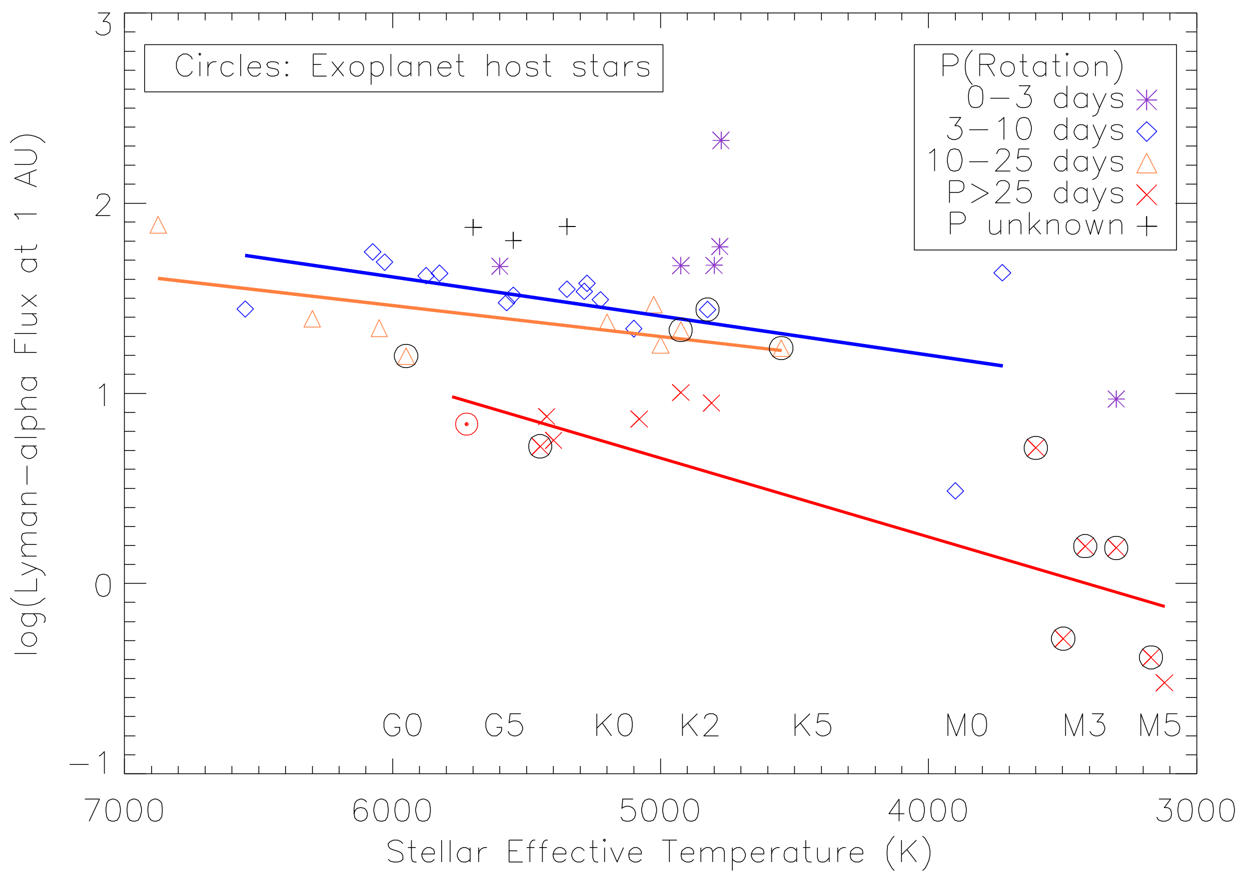
Reconstructed Lyman-α/CaII flux ratio vs. CaII flux



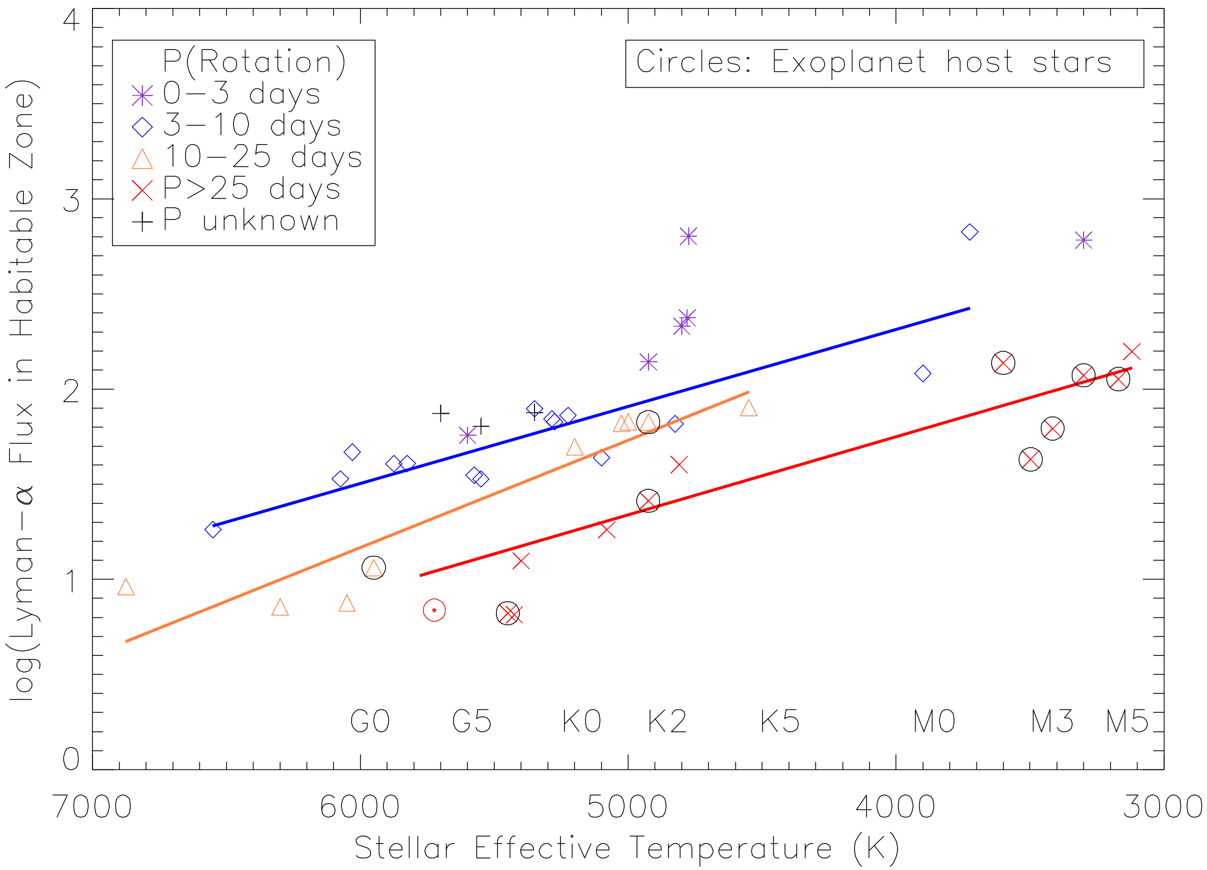
Reconstructed Lyman-α flux/X-ray flux.
f(Lyman-α)/f(X-ray)=A+B*f(Lyman-α)



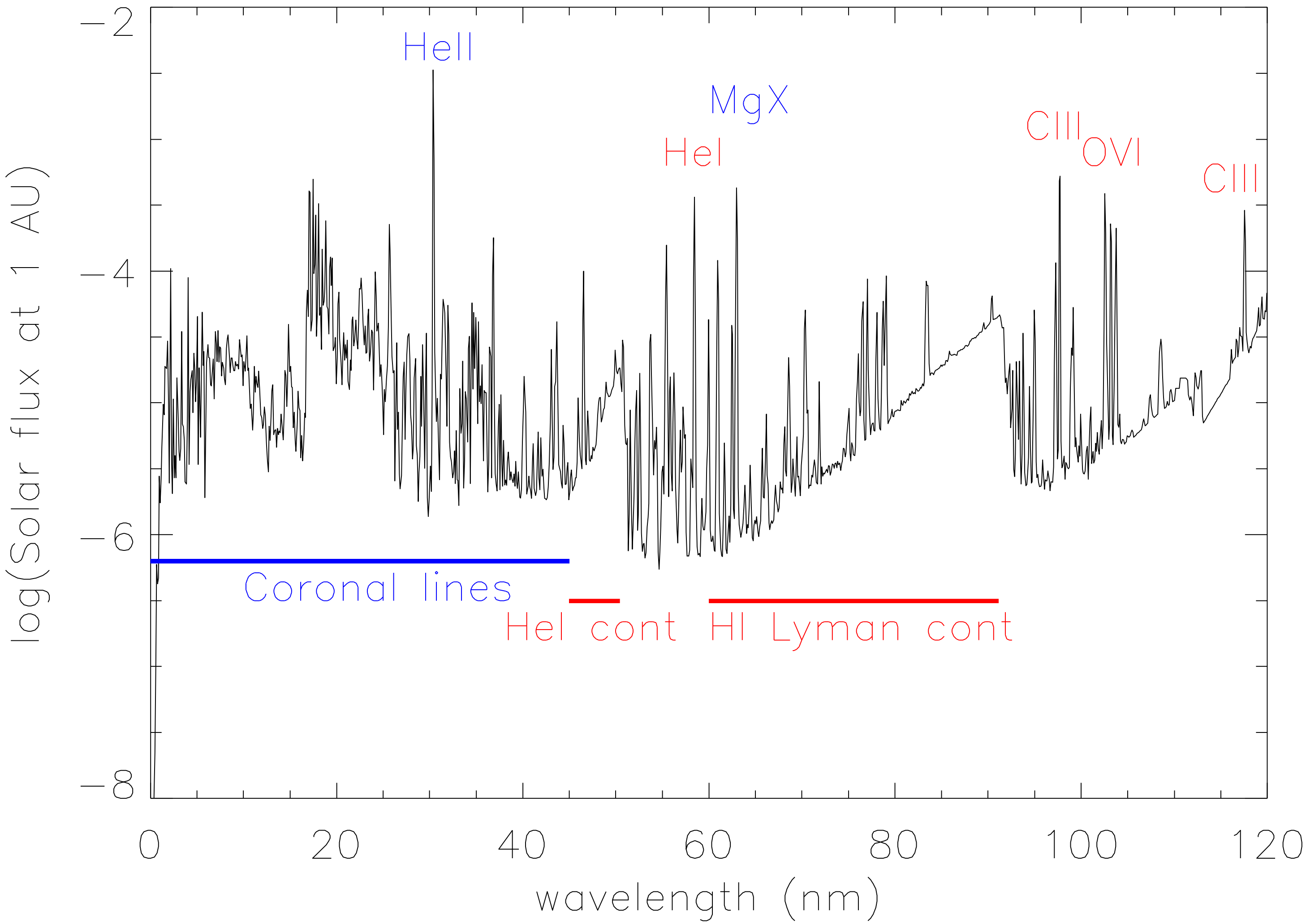
F(Lyα) at 1 AU vs. T_{eff} and P_{rot}



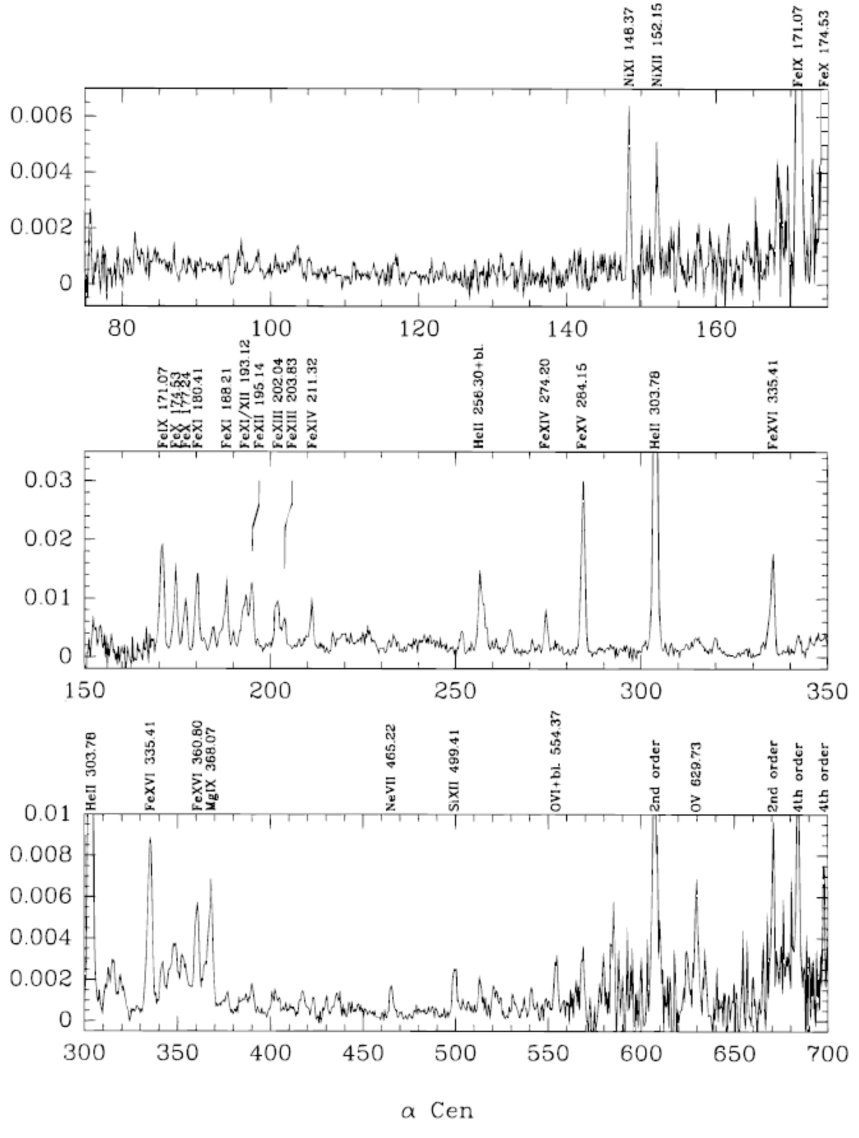
F(Lyα) in the Habitable Zone vs T_{eff} and P_{rot}



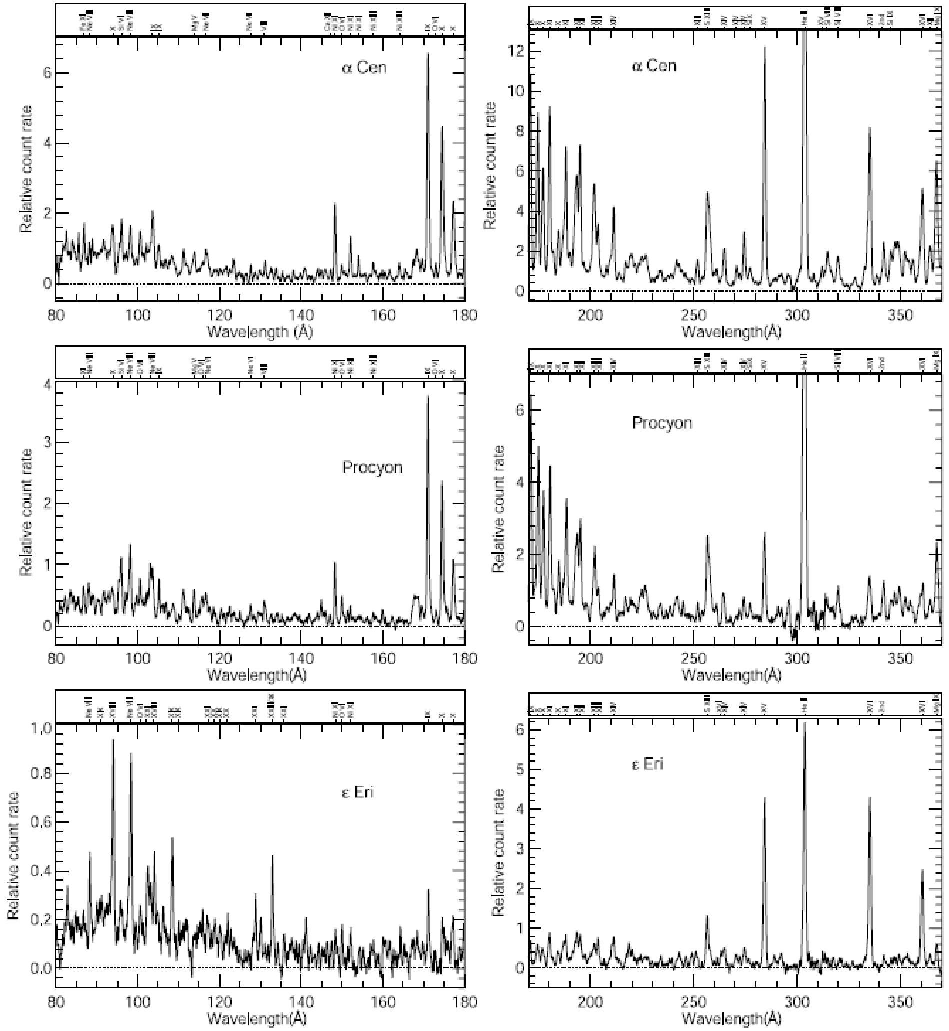
Extreme-ultraviolet (EUV) Portion of the Quiet Sun Spectrum



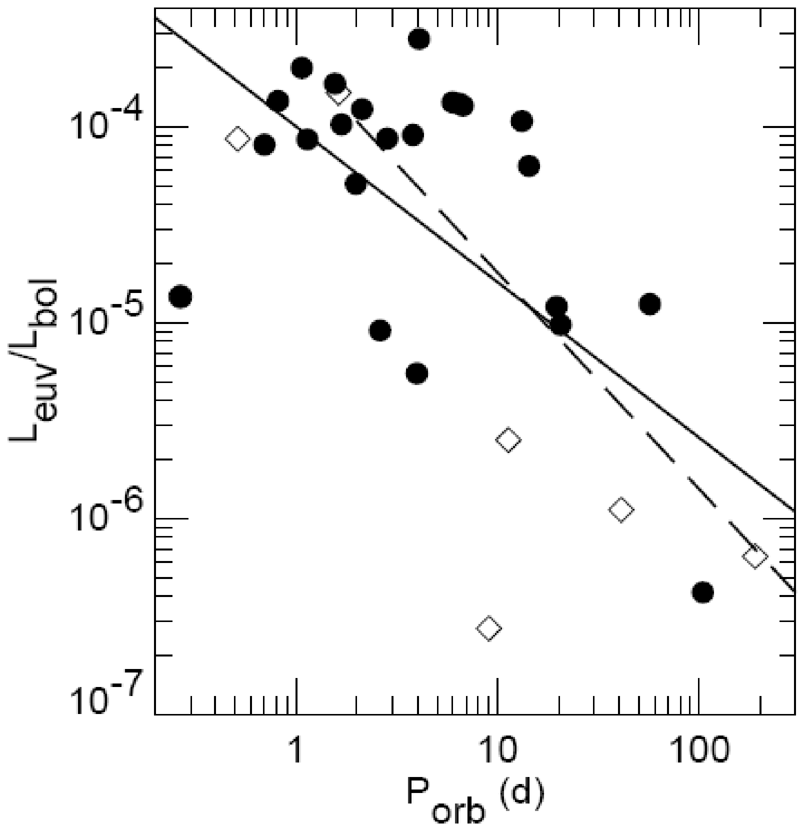
EUVE spectrum of α Cen A+B(G0 V + K1 V) at 1.3 pc (Craig et al. (ApJS 113, 131 (1997))

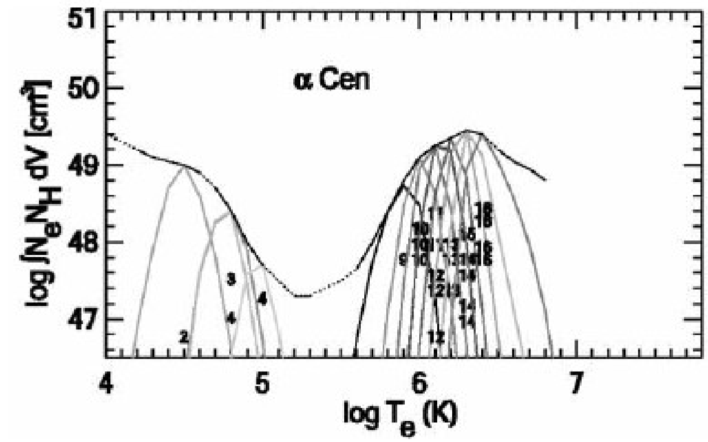


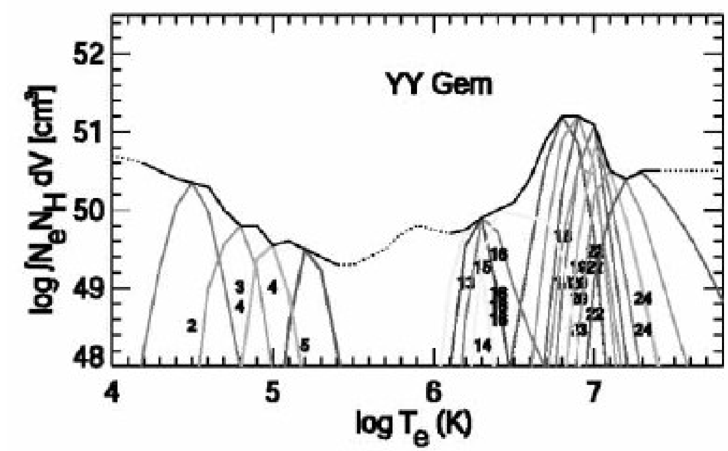
EUVE spectra of F5-K2 stars (Sanz-Forcada et al. ApJS 145,147 (2003)



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



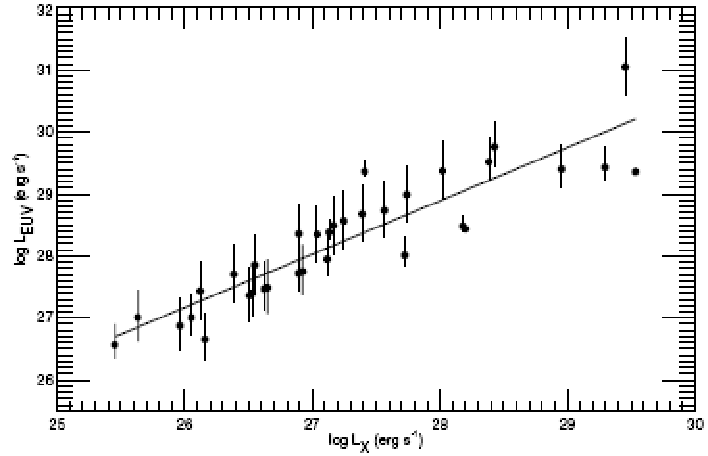


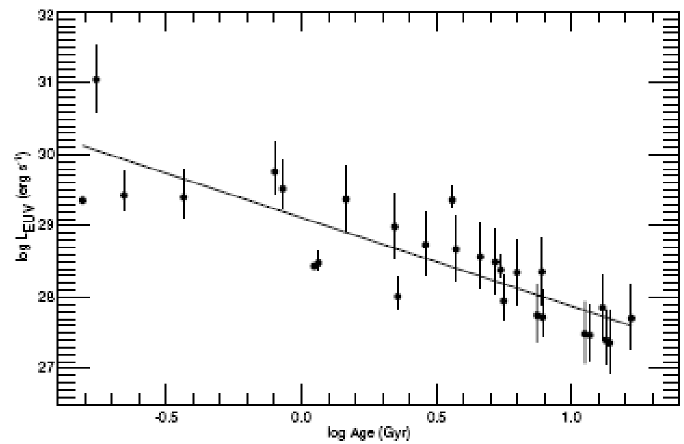


Scaling of EUV flux from observed X-ray flux (Sanz-Forcada et al. (A+A 532, A6 (2011))

- 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.

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

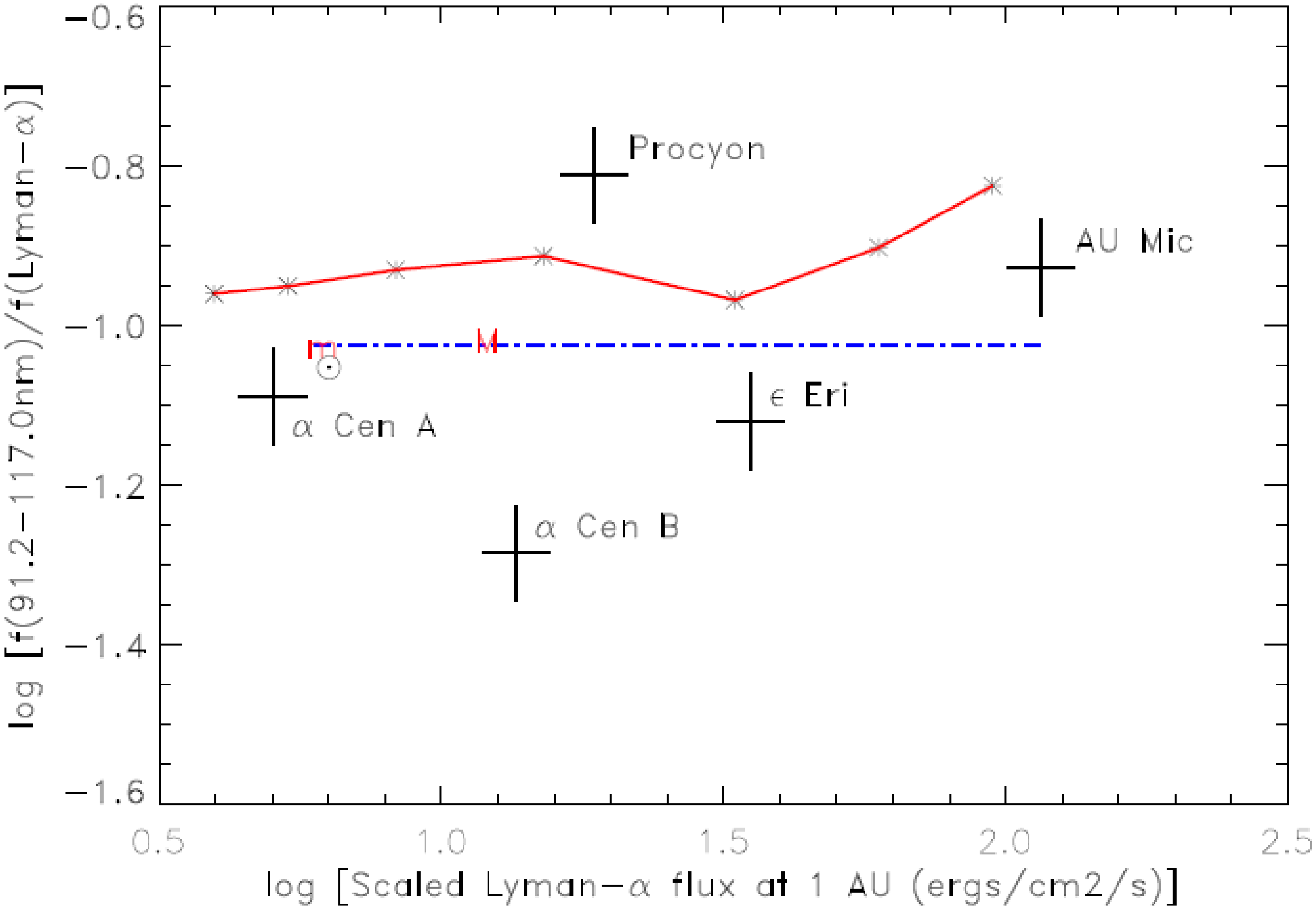




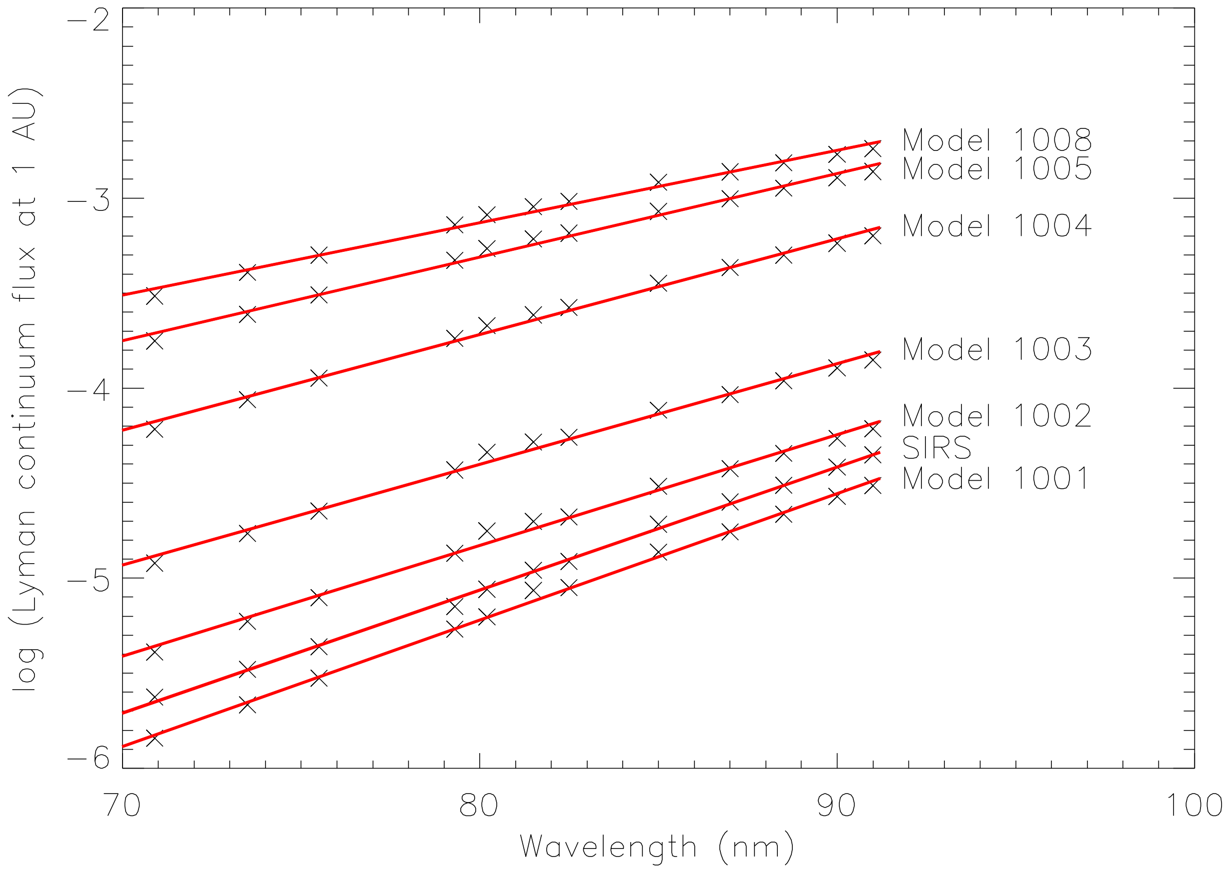
Separate the EUV into wavelength bands with different techniques for testing (Linsky et al. ApJ 766, 69 (2013))

- 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 EUV 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.

Comparison of stellar fluxes in the 91.2-117nm band from FUSE (Redfield et al. 2002) with Fontenla models (red line) and solar spectra (SIRS and SEE). Blue line is best fit to the data.

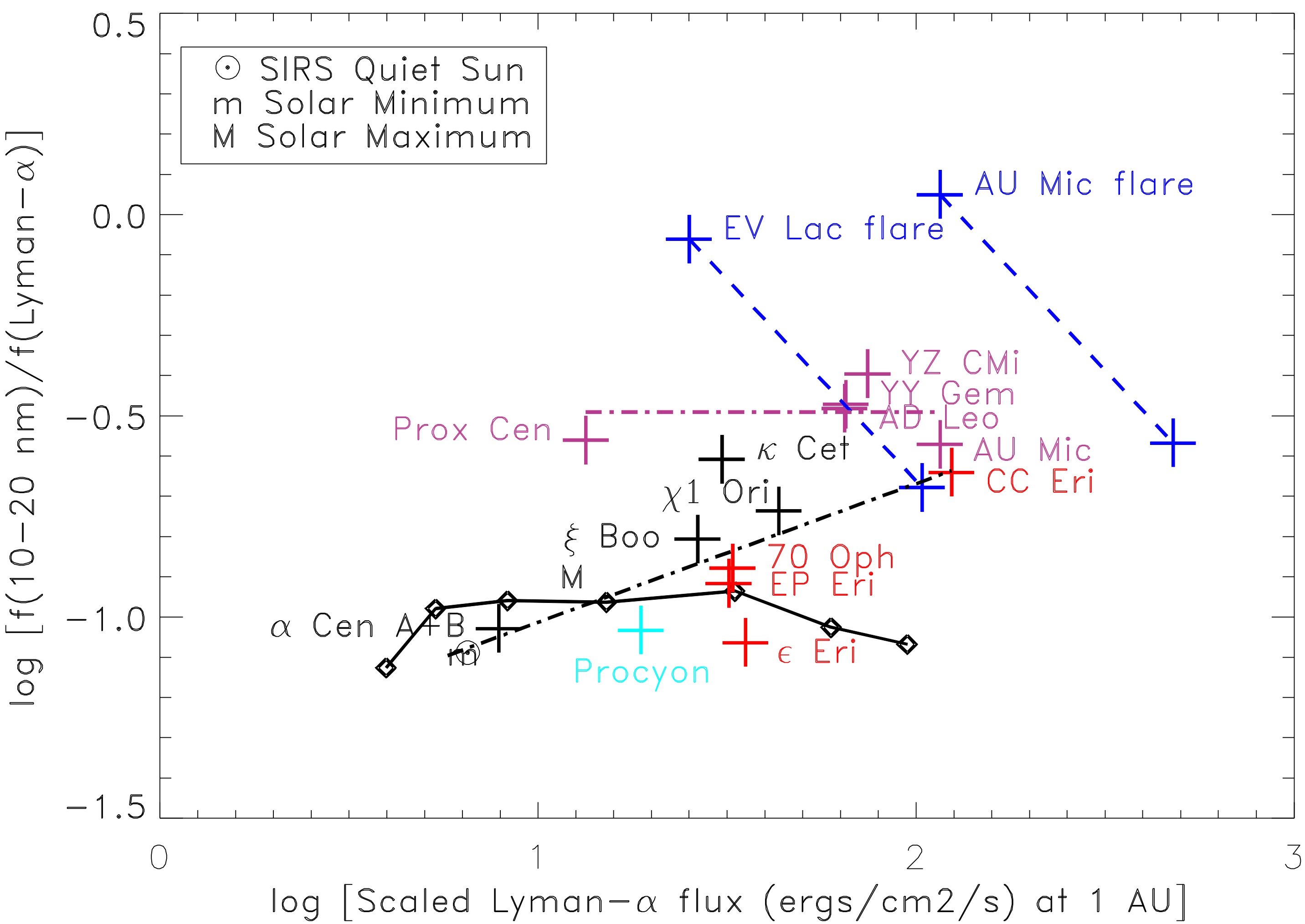


Solar Hydrogen Lyman Continuum Flux excluding emission lines

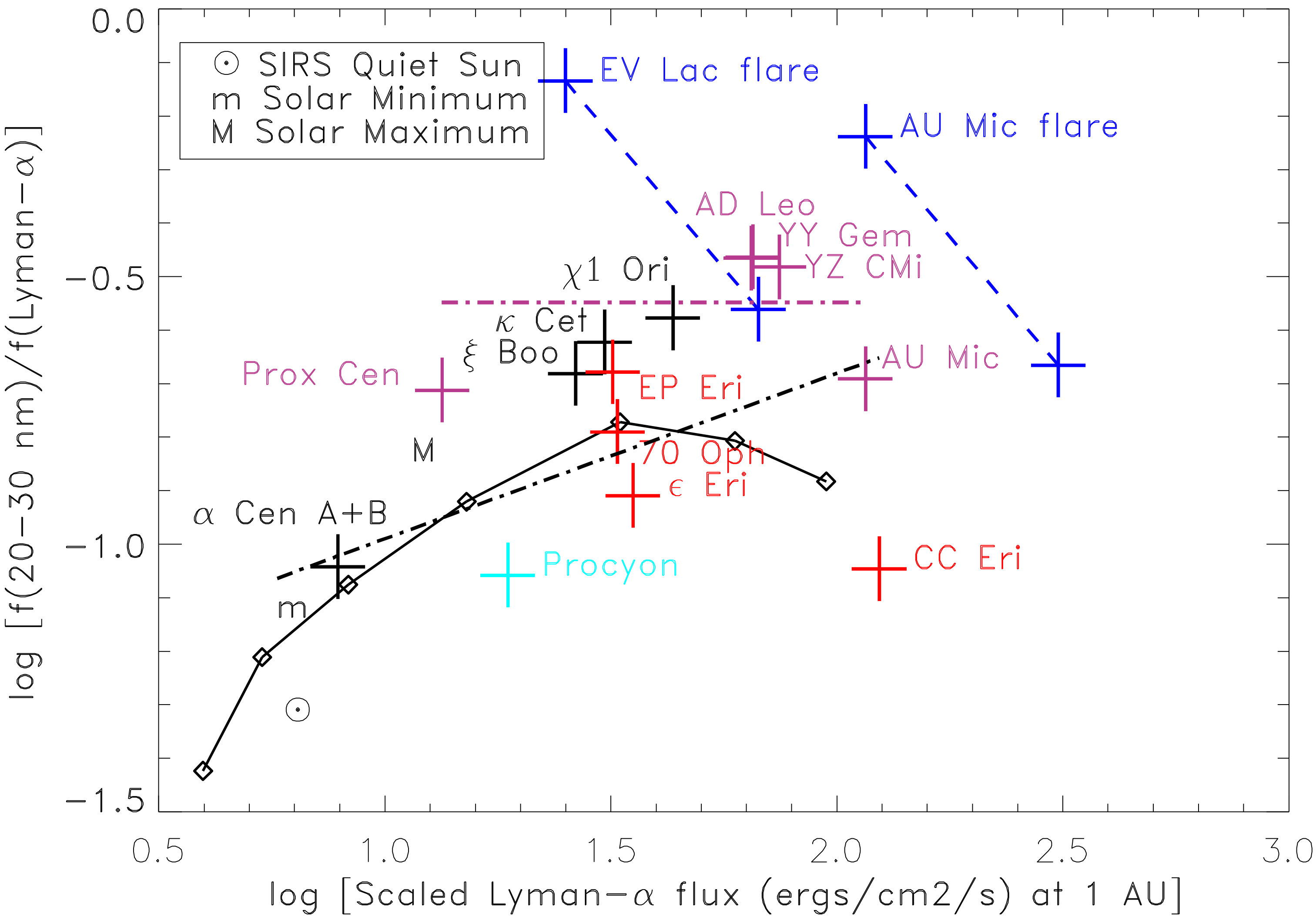


f(Lyman-cont)/f(Lyman-α)=0.052 (Model 1001) to 0.175 (Model 1008). T(color)=12175 K (Model 1001) to 17,702 K (Model 1008).

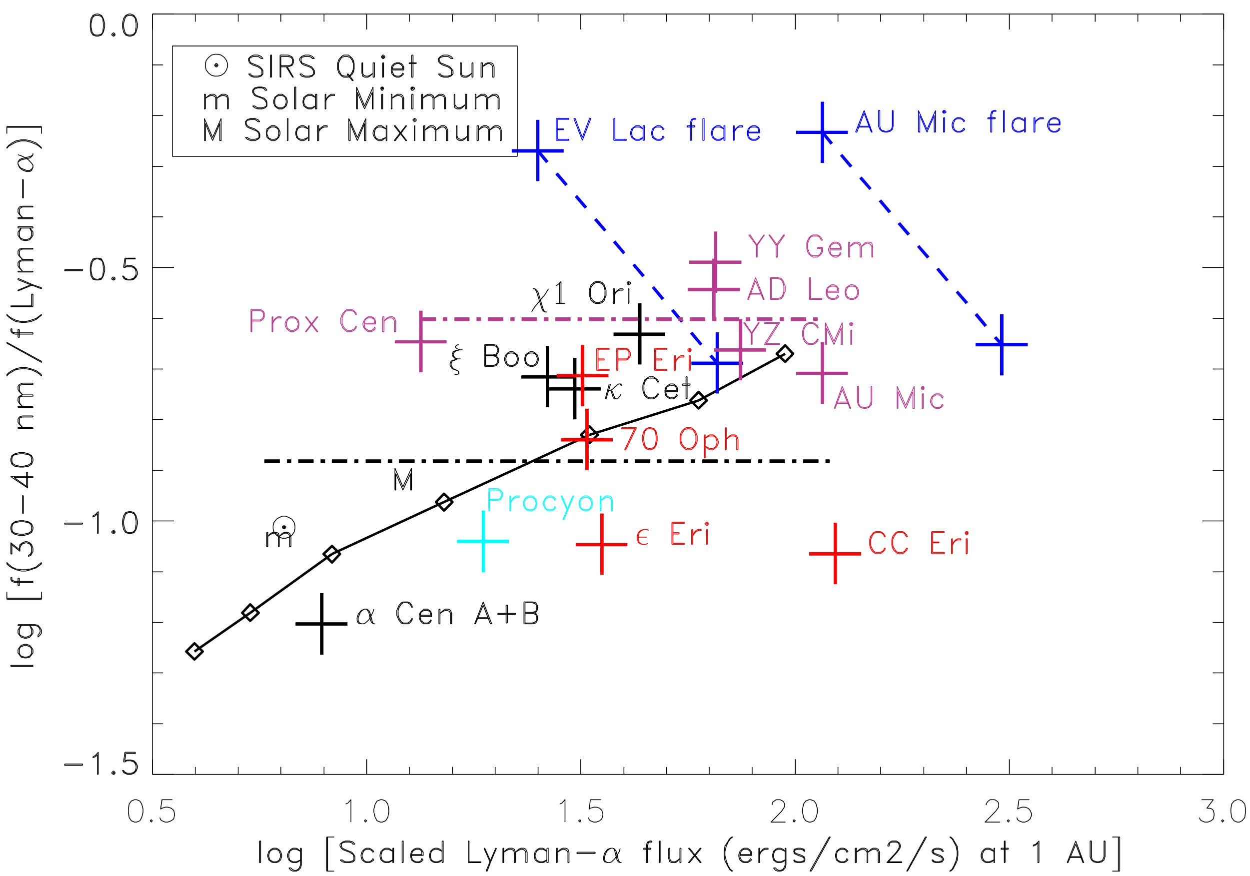
f(10-20nm)/f(Lyα) vs f(Lyα) scaled by R^2 compared to solar semi-empirical models (Linsky et al. ApJ 780, 61 (2014))



Same for f(20-30nm)/fLyα)

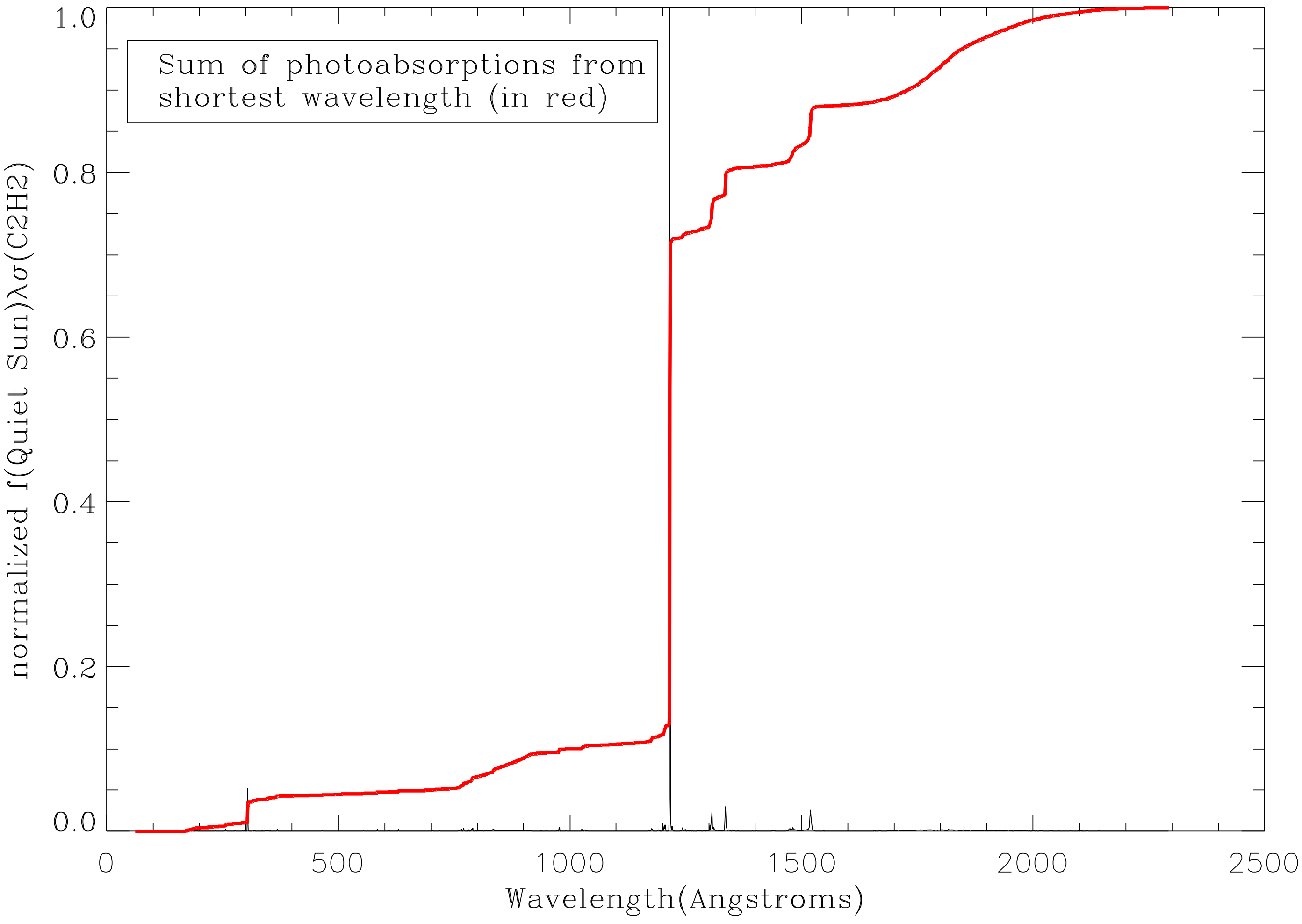


Same for f(30-40nm)/f(Lyα)

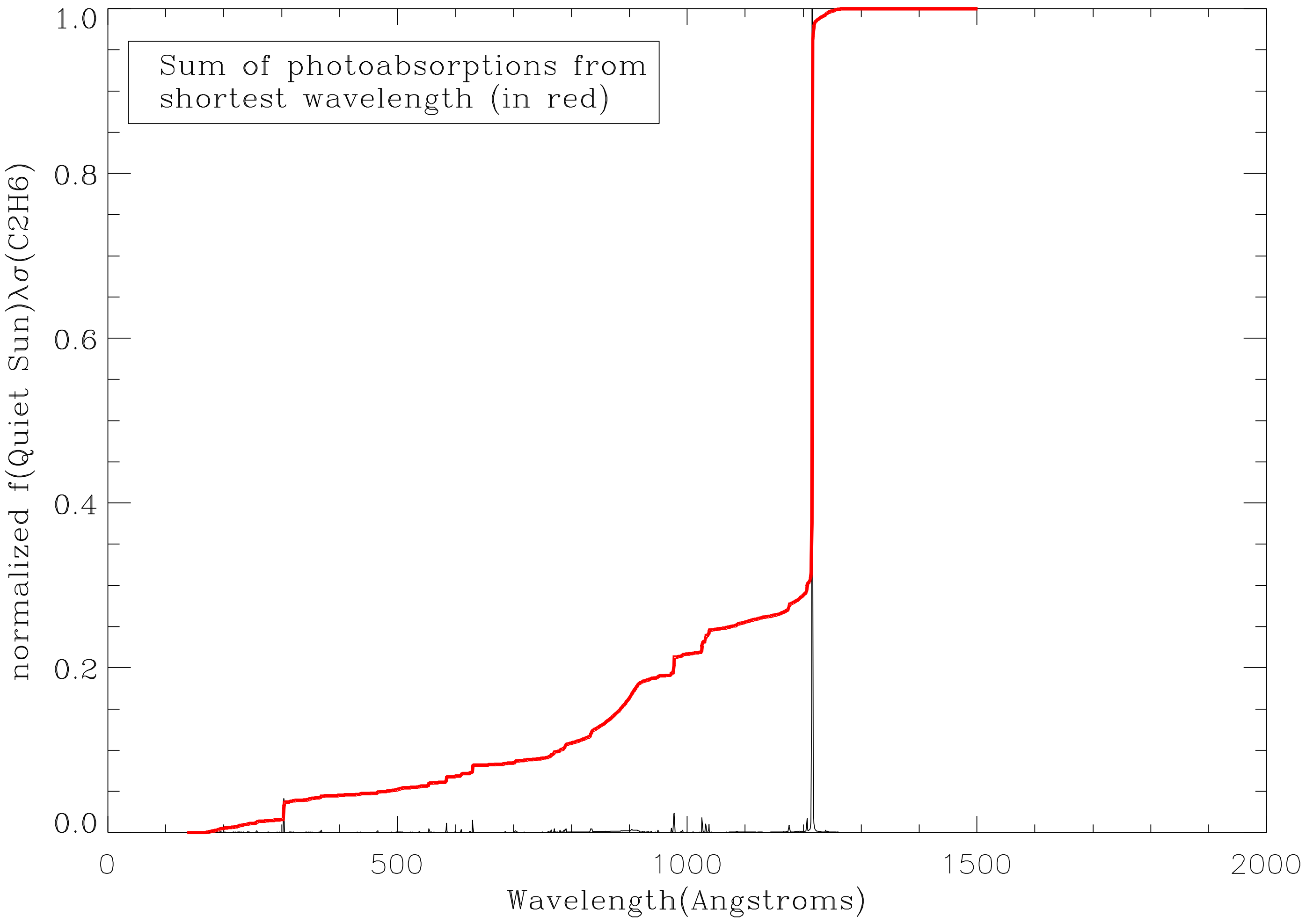


Additional slides

Summation of the Photoabsorption of C_2H_2 by the Quiet Sun Spectrum

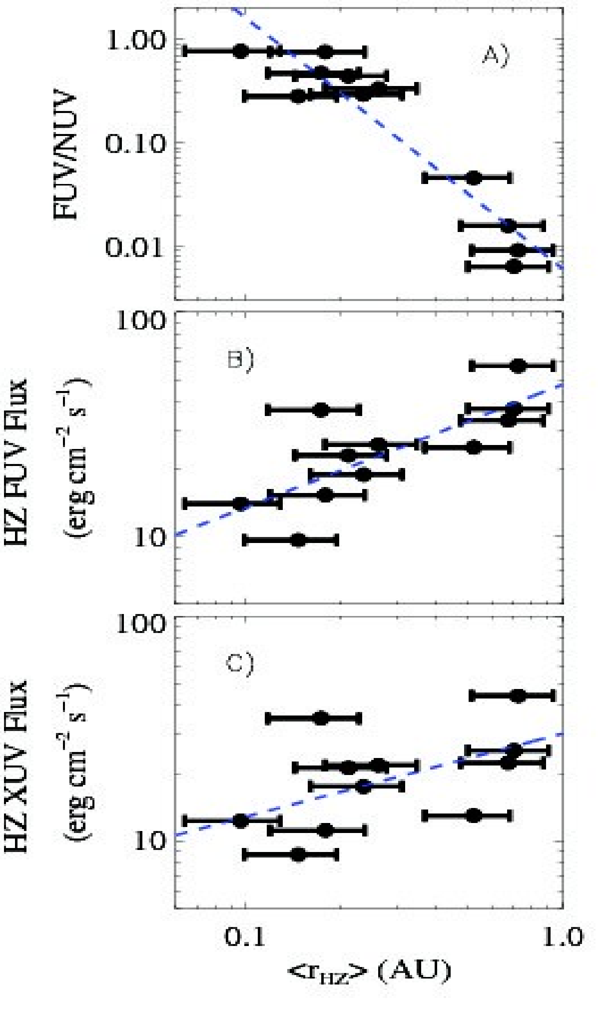


Summation of the Photoabsorption of C_2H_6 by the Quiet Sun Spectrum

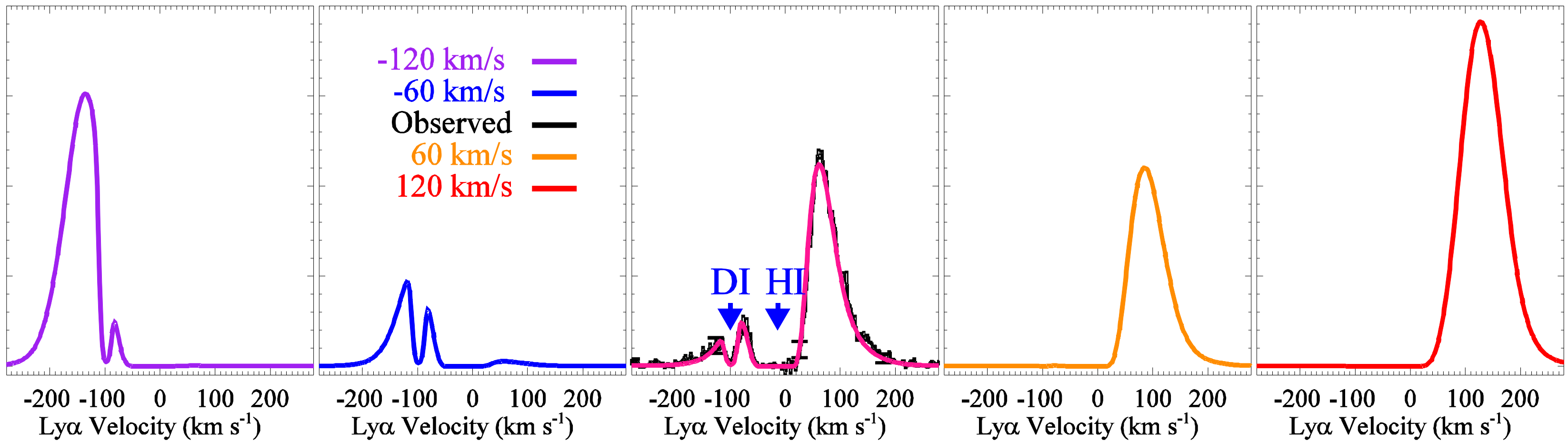


Fluxes and flux ratios for the MUSCLES stars as seen by hypothetical exoplanets

- Fluxes and flux ratios in the centers of the HZs for each of the MUSCLES stars.
- France et al. (in preparation)

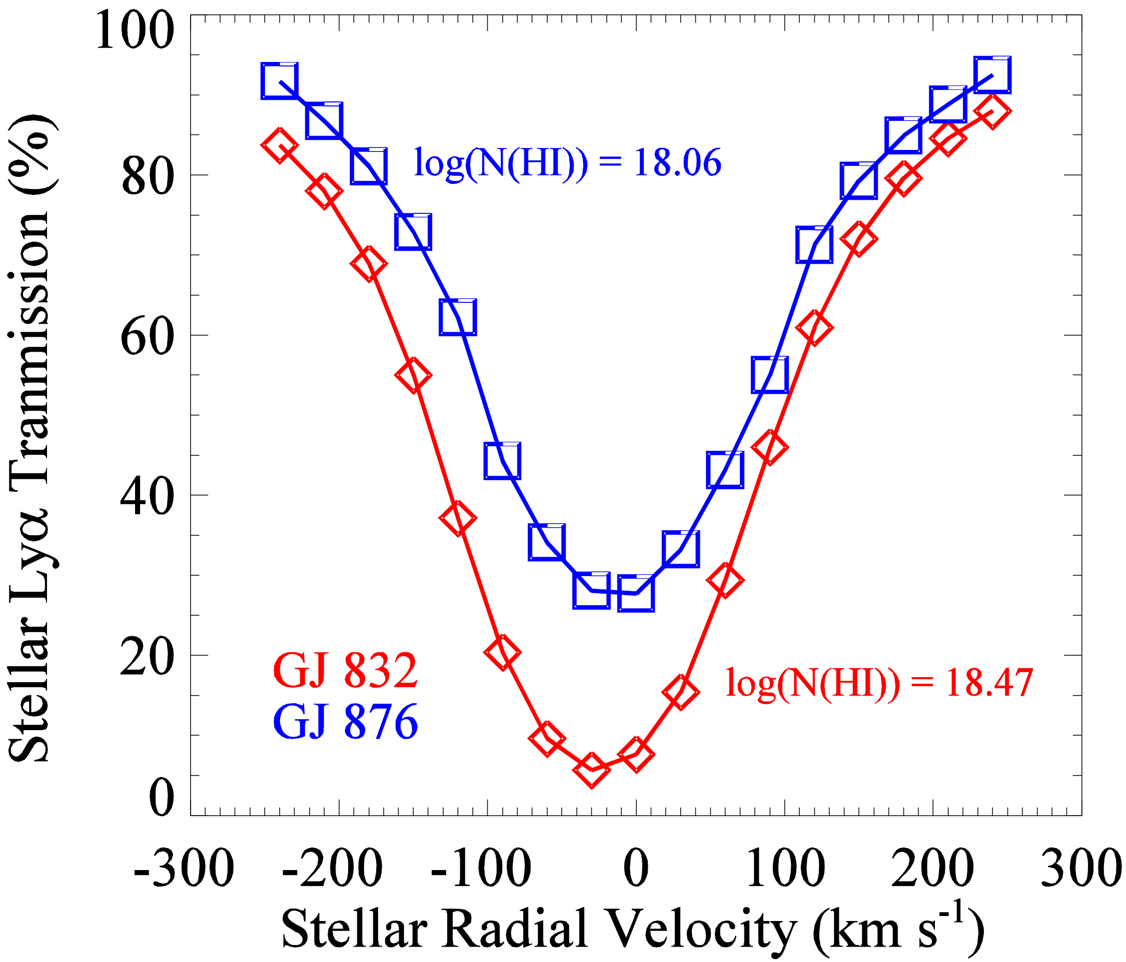


Comparison of the “observed” Lyman-α profile from the M1.5 V star GJ832 through the ISM

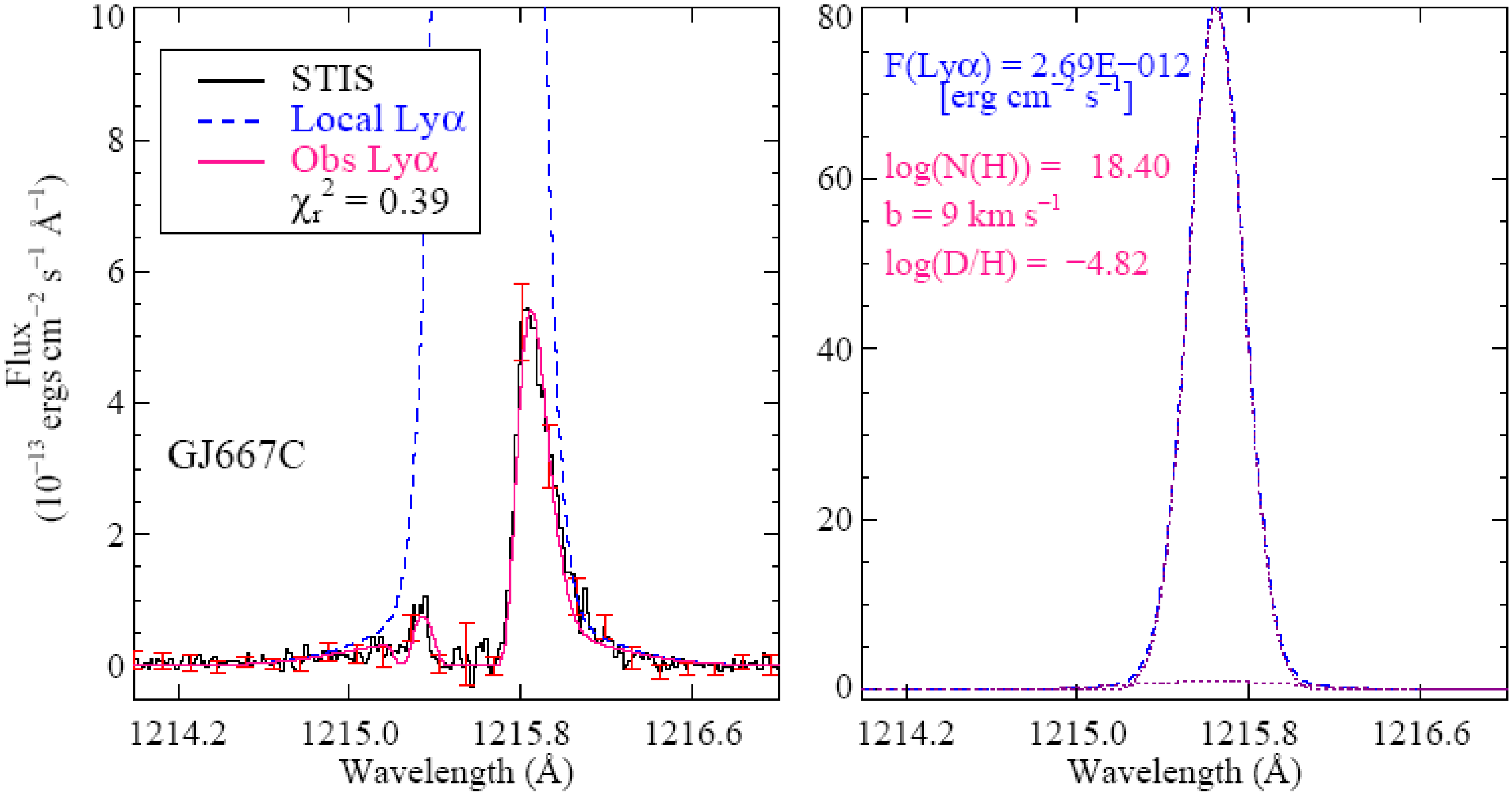


- Center panel: stellar RV=18 km/s, Red profile is observed. Black profile is intrinsic folder through the ISM.
- Other panels: intrinsic profile folder through ISM with assumed stellar RVs. Multiply flux by 4.

Lyman-α transmission through the ISM as a function of assumed stellar radial velocity for two M dwarfs



Observed and reconstructed Lyman-α flux for GJ667C (M1.5V)

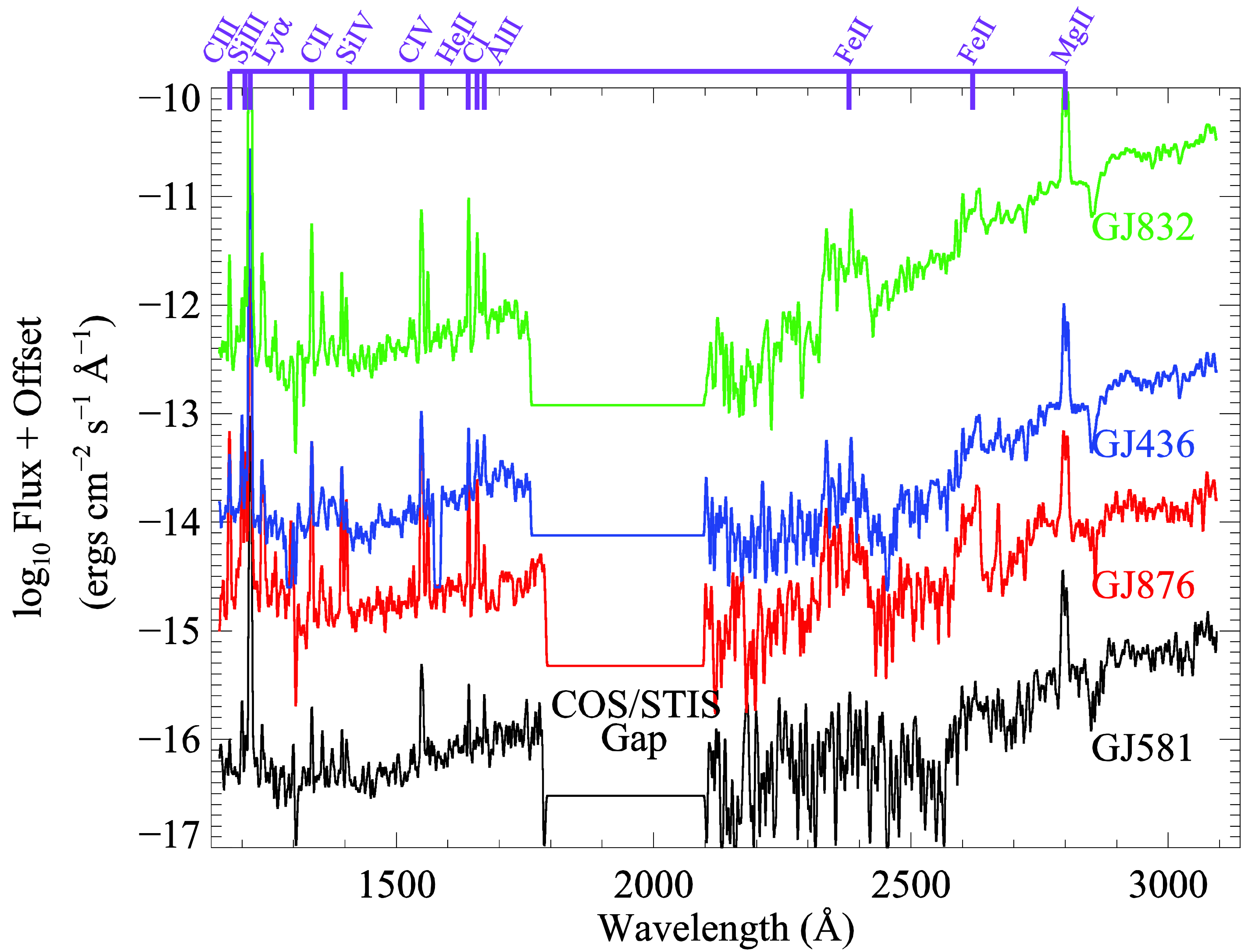


2 exoplanets at 0.05 and 0.12 AU.

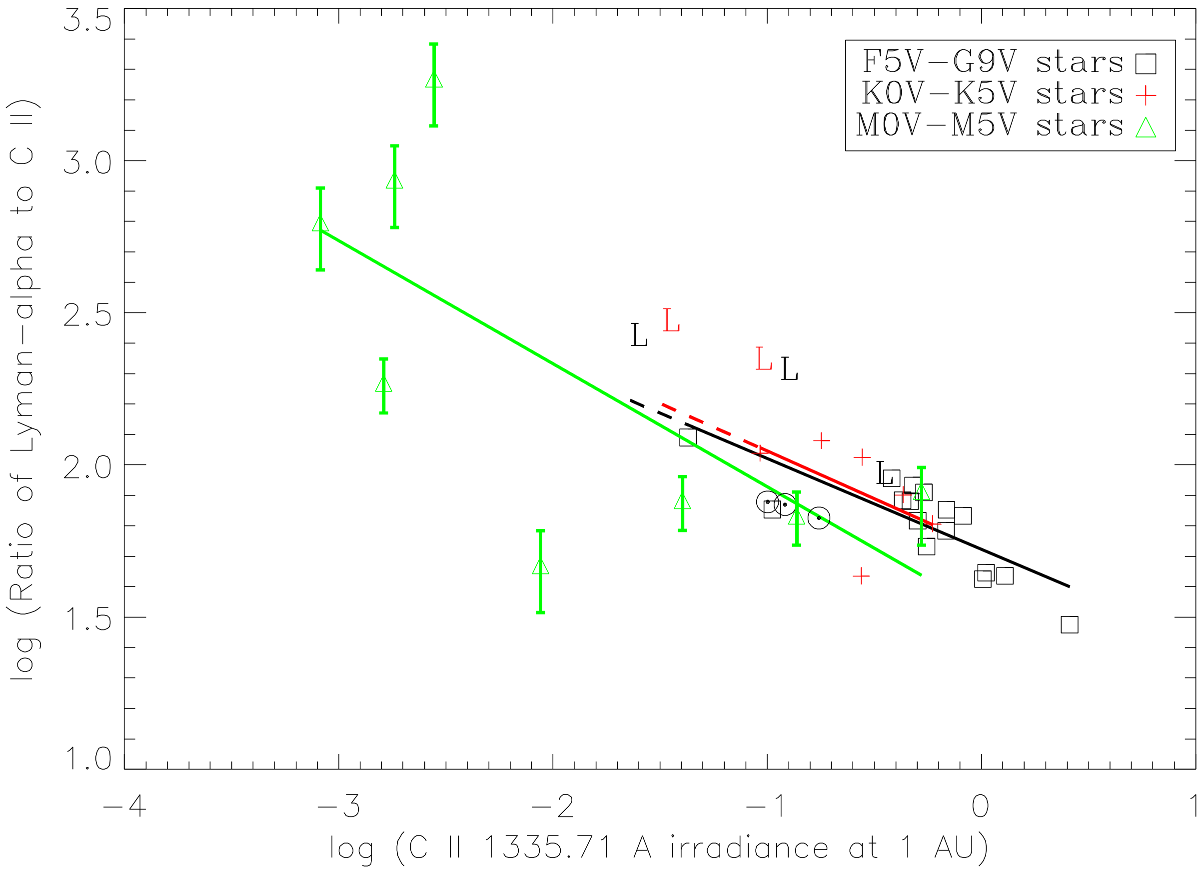
Solar models and computed spectral irradiance (solar flux)

- Semi-empirical models computed by Fontenla et al. (2011) to fit X-ray to far-IR emission from regions on the Sun with different emission levels (heating rates).
- 1-D non-LTE radiative transfer models with 21 elements in 50 ionization stages with T(h) determined to fit spectra of each solar feature.
- Models 1001 (very quiet)-1008 (bright active region) for chromosphere and transition region up to T=250,000 K.
- Models 1011-1018 for corresponding corona and TR with T>250,000 K.
- There are no stellar models with computed UV and EUV fluxes of this quality. Computations are underway.

Four M dwarfs with exoplanets observed by COS (France et al. ApJ 763, 149 (2013)). Resolution λ/17,000.

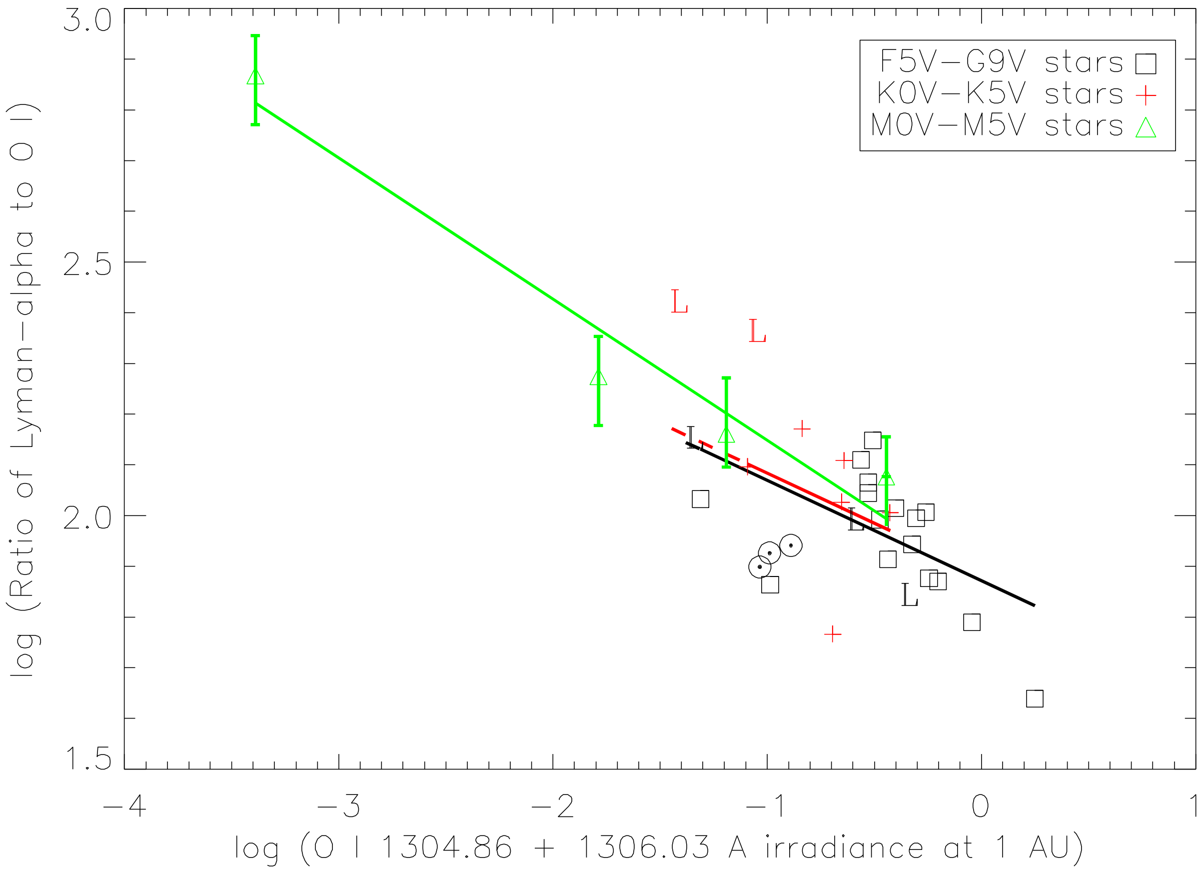


The reconstructed Lyman-α/C II flux ratio depends smoothly on the observed C II flux and spectral type



C II formed near 10,000 K and Lyman-α formed near 10,000 K.

The reconstructed Lyman-α/O I flux ratio depends smoothly on the observed O I flux and spectral type

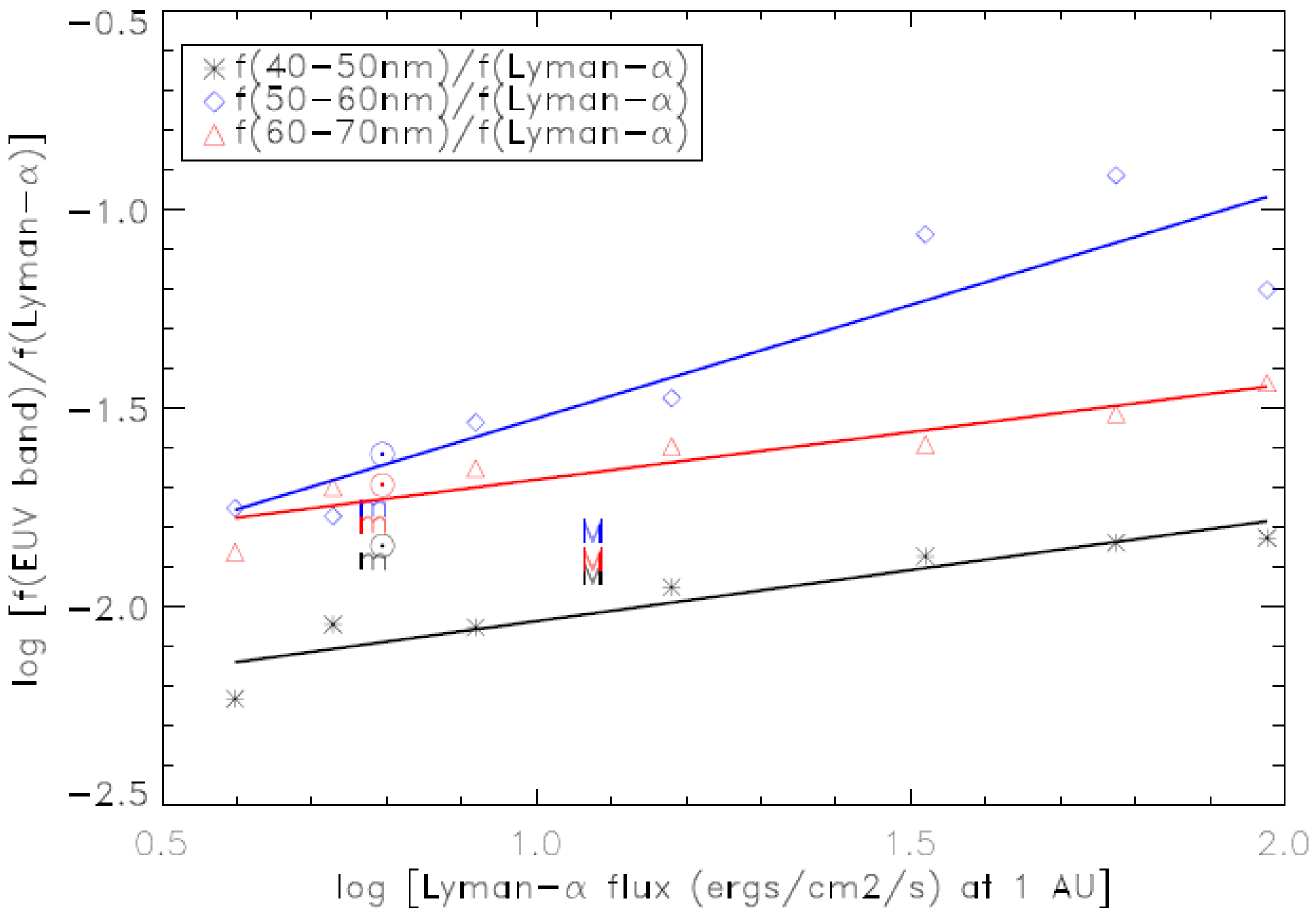


O I formed near 6,000 K and Lyman-α formed near 10,000 K.

Dispersions in Lyman-α flux about the fit lines if know only T_{eff} and rotation rate

Distance From star	Rotation Period (d)	Mean Dispersion	RMS Dispersion
1 AU	3-10	41%	74%
1 AU	10-25	32%	42%
1AU	>25	85%	100%
HZ	3-10	35%	47%
HZ	10-25	37%	44%
HZ	>25	43%	52%

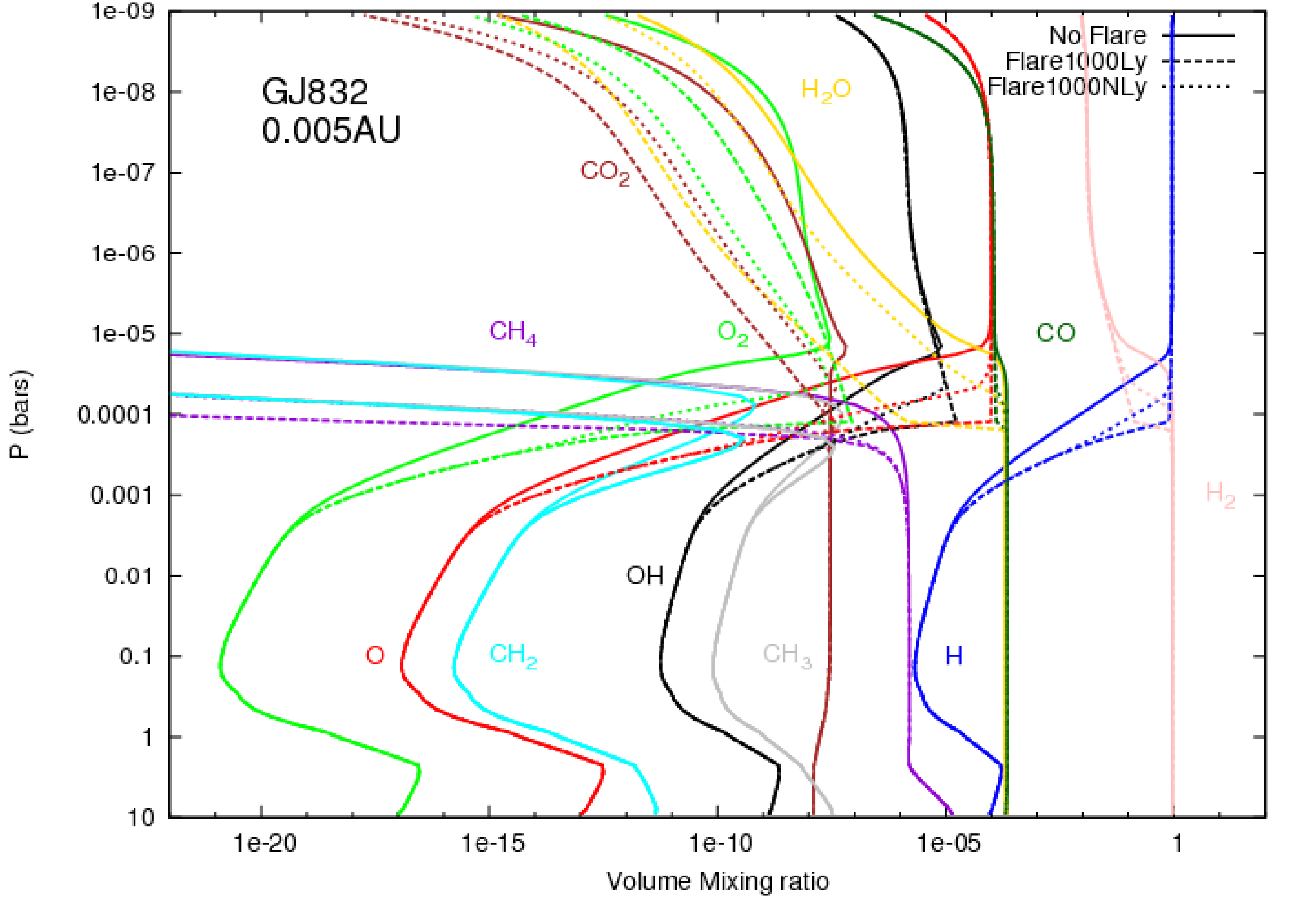
Comparison of observed solar fluxes with semi-empirical models of solar regions

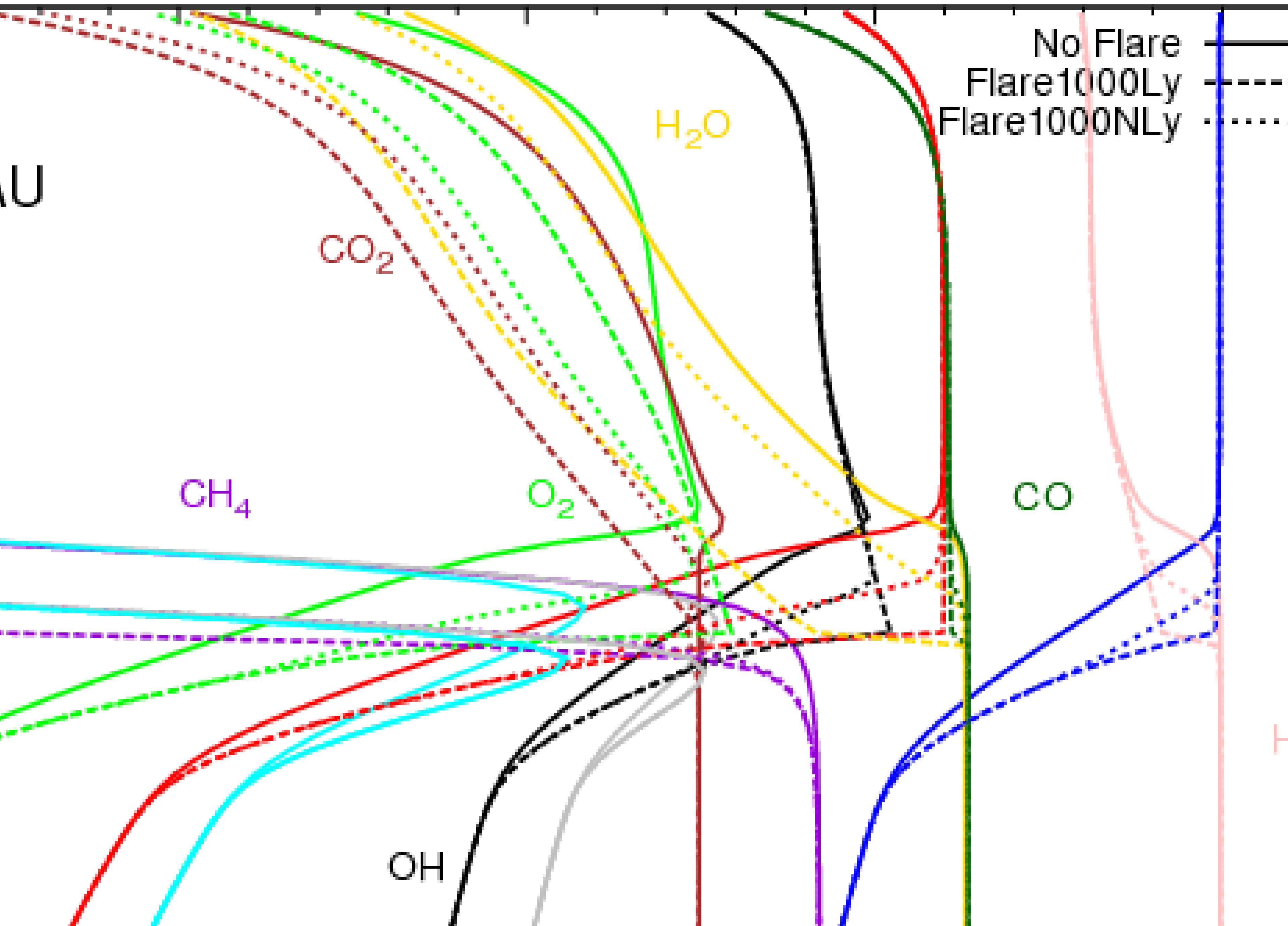


Two Solar EUV Reference Spectra

- SIRS (Solar Irradiance Reference Spectrum). Quiet Sun spectra 0.1-2400nm (March-April 2008) based on data from the TIMED spacecraft and rocket observations. (Woods et al. 2005).
- SEE data set for solar minimum (2008 day 105) and solar maximum (2002 day 76). Spectra obtained with the SEE (Solar EUV Experiment) on the TIMED spacecraft with version 11 calibration.
- Both data sets have best available absolute flux calibrations.

Photochemistry of an M dwarf atmospheres with and without Lyman-α (Miguel et al (2015))





No Flare
Flare1000Ly
Flare1000NLy
AU
H2O
CO2
CH4
O2
CO
OH

Exoplanet parameters: radius, orbital period and distance, density, habitability (liquid water, atmospheric chemical composition, radiation environment, etc.)

- Earth size: <1.25 R_E
- SuperEarth size: 1.25-2.0 R_E
- Neptune size: 2-6 R_E
- Jupiter size: 6-15 R_E

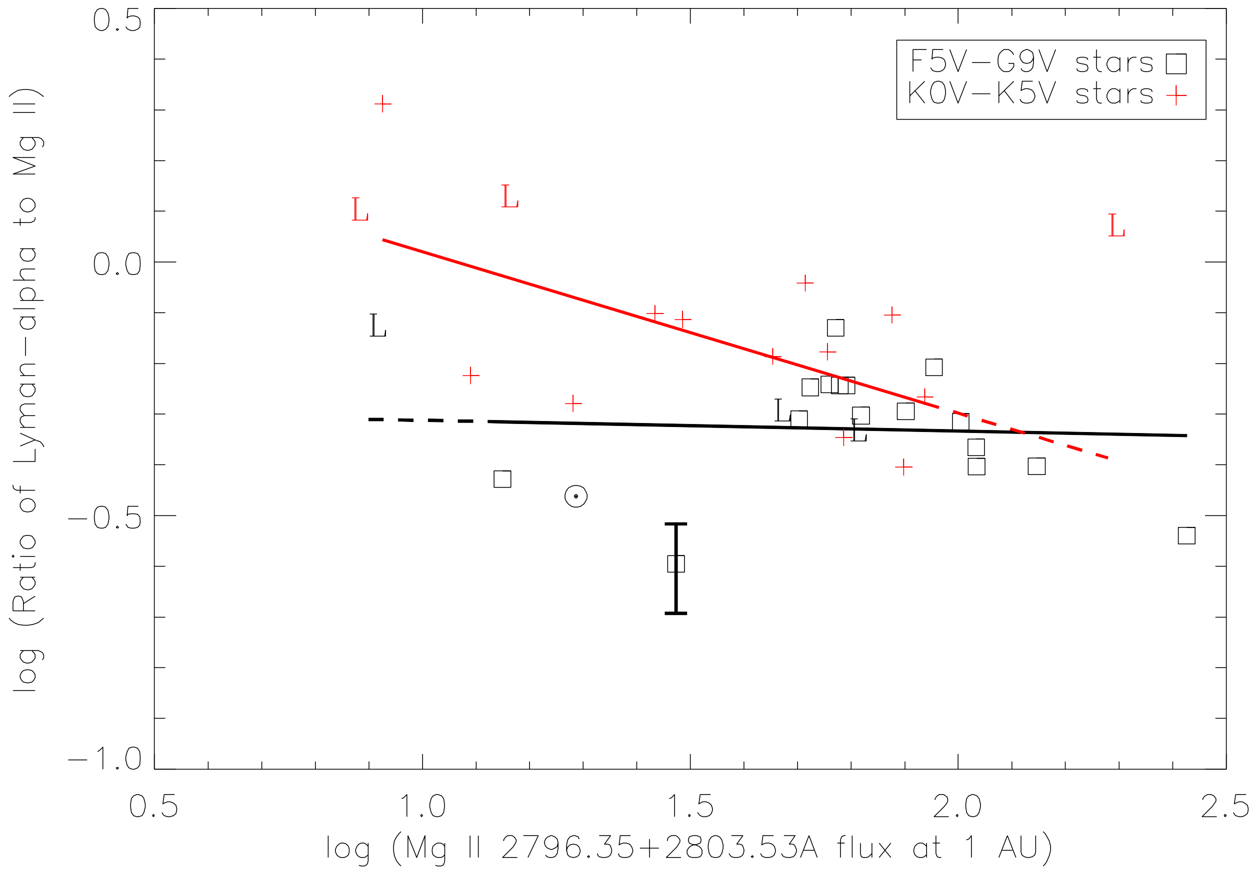
The exoplanetary system of the G star Kepler-11

Exoplanet	M/M_E	R/R_E	P(days)
Kepler-11b	4.35	1.98	10.3
Kepler-11c	13.71	3.16	13.03
Kepler-11d	6.19	3.45	22.6
Kepler-11e	8.52	4.54	32.0
Kepler-11f	2.33	2.62	46.7
Kepler-11g	306	3.67	118.4

Some low-mass exoplanets

Exoplanet	Star Type	M/M_E	R/R_E	P(days)
KOI-55c	sdB	0.68	0.88	0.343
Kepler-42d	--	0.97	0.57	49.5
GJ581d	M2.5V	1.97	--	3.15
HD20794c	G8V	2.45	--	40.1
HD20794b	G8V	2.74	--	18.3
HD215152b	K0	2.81	--	7.3
Kepler-20e	G8	3.13	0.88	6.1

The reconstructed Lyman-α/Mg II flux ratio depends smoothly on Mg II line flux for F5 V to K2 V stars



Mg II formed near 5,000 K and Lyman-α formed near 10,000 K. Both lines very optically thick.

Dispersions in R(line) = f(Lyman-α)/f(line) for stars with near solar abundances

Spectral Types	Spectral Line	Mean Dispersion	RMS Dispersion
F5 V-G9 V	C IV	18%	22%
K0 V-K5 V	C IV	16%	18%
M0 V-M5 V	C IV	118%	159%
F5 V-G9 V	Mg II	24%	31%
K0 V-K5 V	Mg II	30%	39%
M0 V–M5V	Mg II	28%	34%