# Quiescent and flaring lyman-$\alpha$ radiation of host stars and effects on exoplanets

**Jeffrey L. Linsky[1], Kevin France[2], Yamila Miguel[3] and Lisa Kaltenegger[4]**

[1] JILA, University of Colorado and NIST, Boulder CO 80309-0440 USA
email: `jlinsky@jila.colorado.edu`

[2] LASP, University of Colorado, Boulder CO 80309-0600 USA
email: `kevin.france@colorado.edu`

[3] Laboratoire Lagrange, Observatoire de la Côte d'Azur, CNRS, Blvd de l'Observatoire, CS 3422, 06304 Nice cedex 4, France
email: `yami.miguel@gmail.com`

[4] Carl Sagan Institute, Cornell University, Ithaca NY 14853 USA
email: `lkaltenegger@astro.cornell.edu`

**Abstract.** Lyman-$\alpha$ radiation dominates the ultraviolet spectra of G, K, and M stars and is a major photodissociation source for $H_2O$, $CO_2$, and $CH_4$ in the upper atmospheres of exoplanets. We obtain intrinsic Lyman-$\alpha$ line fluxes for late-type stars by correcting for interstellar absorption or by scaling from other spectroscopic observables. When stars flare, all emission lines brighten by large factors as shown by *HST* spectra. We describe photochemical models of the atmosphere of the mini-Neptune GJ 436b (Miguel *et al.* 2015) that show the effects of flaring Lyman-$\alpha$ fluxes on atmospheric chemical abundances.

**Keywords.** stellar chromospheres, energetic flares, planets: atmospheric chemistry

## 1. The Importance of Ly-$\alpha$ Radiation

Since photodissociation and photoionization play critical roles in the chemistry of exoplanet atmospheres (e.g., Kopparapu, Kasting, & Zahnle 2012 and Ribas *et al.* 2010), it is essential to identify and measure the fluxes of the primary spectral features in a host star's spectrum. This is complicated as interstellar neutral hydrogen obscures most of the flux in the important Lyman-$\alpha$ (Ly-$\alpha$) emission line at 121.6 nm and completely absorbs EUV radiation from 91.2 nm down to at least 40 nm, even for nearby stars.

The relative importance of different spectral features in a host star's spectrum that drive an exoplanet's photochemistry is identified in the spectrum of the only star for which a complete short wavelength spectrum can be observed. Figure 1 shows the solar irradiance (flux from the entire Sun) at 1 AU. The near-ultraviolet (NUV, $\lambda$ = 170–320 nm) radiation is emitted in the solar photosphere and the far-ultraviolet (FUV, $\lambda$ = 117–170 nm) radiation is emitted primarily in the chromosphere.

The 91.2–117 nm spectral region containing the hydrogen Lyman series and other emission lines formed between 10,000 and 300,000 K was observed by the *Far Ultraviolet Spectrograph Explorer (FUSE)* satellite and is now observable by the *Hubble Space Telescope (HST)* (McCandliss *et al.* 2010; France *et al.* 2014). The extreme-ultraviolet (EUV) spectrum at wavelengths shorter than the hydrogen ionization edge (91.2 nm) consists of hydrogen and helium continua and emission lines formed in the chromosphere, transition region, and corona (mostly at wavelengths shorter than 40 nm).
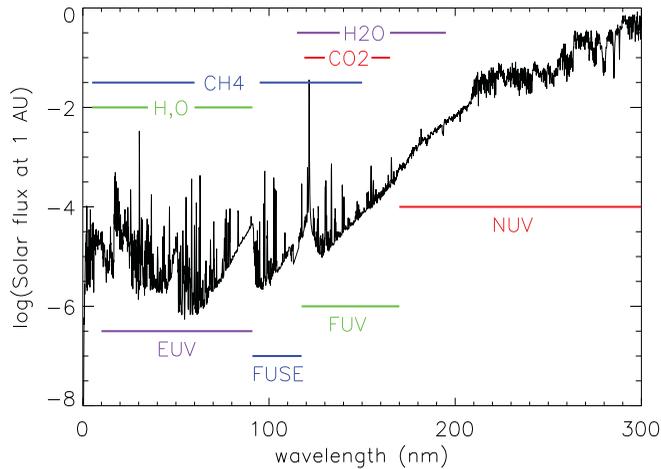
**Figure 1.** The quiet Sun irradiance spectrum (erg cm$^{-2}$ s$^{-1}$) observed April 10–16, 2008, with the Solar Radiation and Climate Experiment (SORCE) on the SOLSTICE II satellite (Snow *et al.* 2005 and Woods *et al.* 2009). Different spectral ranges are indicated as well as the overlap with the photodissociation and photoionization cross-sections of the $H_2O$, $CO_2$, and $CH_4$ molecules and hydrogen and oxygen atoms.

The Ly-$\alpha$ line of hydrogen is the brightest emission line in the solar UV spectrum, and the overlap of Ly-$\alpha$ with the photodissociation cross sections of important molecules in exoplanet atmospheres (e.g., $H_2O$, $CO_2$, and $CH_4$) demonstrates that the Ly-$\alpha$ line is an essential driver of exoplanet photochemistry. In the solar spectrum, the Ly-$\alpha$ flux is about 30% of the FUV flux but only 0.026% of the total FUV+NUV flux, because the warm photosphere produces strong NUV emission. For stars cooler than the Sun, in particular M dwarfs, the cool photosphere produces very little NUV and FUV flux (see Figure 2). As a result, France *et al.* (2012) find for the M4 V star GJ 876 that the stellar Ly-$\alpha$ flux is 2.3 times greater than the FUV flux (excluding Ly-$\alpha$) and nearly as bright as the entire NUV+FUV flux. However, most of the stellar Ly-$\alpha$ flux is unobservable because of interstellar Ly-$\alpha$ absorption and must be reconstructed or estimated to compute credible photochemistry models of exoplanet atmospheres.

## 2. Reconstructing the Stellar Ly-$\alpha$ Emission Line

We have developed five techniques for reconstructing stellar Ly-$\alpha$ emission lines with a range of accuracy depending on the quality of the observed Ly-$\alpha$ line profile and knowledge of the interstellar medium parameters

• Wood *et al.* (2005) showed that with a high-resolution spectrum that includes the Ly-$\alpha$ lines of hydrogen and deuterium (–80 km/s from the H line) and lines of heavy ions (e.g., Mg II and Fe II), one can compute the interstellar parameters along the line of sight to the star and infer the star's intrinsic Ly-$\alpha$ emission line. The D Ly-$\alpha$ line plays a critical role in the analysis since the excitation and ionization of H and D are the same and the D line is optically thin or nearly so while the H line for nearby lines of sight is 670,000 times as optically thick. Wood *et al.* (2005) computed intrinsic Ly-$\alpha$ line profiles and fluxes for 40 stars with estimated uncertainties < 15%. This technique is limited to interstellar column densities log N(HI)< 18.7, corresponding to distances less than about 40 pc. For larger column densities, the broad interstellar H line covers the D line.

• The low resolution and S/N spectra of M dwarf host stars cannot resolve the D Ly-$\alpha$ line. For such data (see Figure 3), France *et al.* (2013) developed a reconstruction technique that determines the intrinsic Ly-$\alpha$ line profile parameters (two Gaussians with
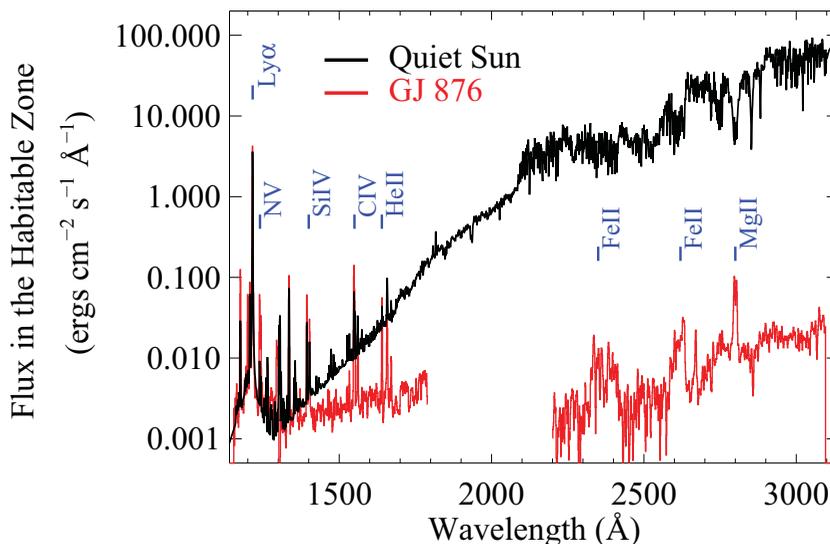
**Figure 2.** Comparison of the solar 1150–3140 Å flux incident on the habitable zone for the solar system (solar flux at 1 AU, black) and the observed flux from GJ 876 in its habitable zone (0.21 AU, red). The 1800–2200 Å region from GJ 876 is excluded due to low S/N. The 1150–1450 Å flux is averaged over flare and quiescent observations. Important stellar emission lines are marked. Figure from France *et al.* (2012).

different widths) and the interstellar velocity and N(HI) by fitting the observed Ly-$\alpha$ profile. The excellent fit to the observed Ly-$\alpha$ lines of the five M dwarf host stars in Figure 3 shows the power of this technique. When the interstellar absorption along the line of sight is at a single velocity, the uncertainty in the intrinsic Ly-$\alpha$ flux is similar to that obtained by the first technique, but the uncertainty is larger when the interstellar velocity structure is more complex.

• Models of the solar chromosphere for regions with enhanced chromospheric emission rates (and thus enhanced heating rates) have similar temperature distribution shapes but with the chromospheric temperature rise displaced deeper into the atmosphere (Fontenla *et al.* 2011) and thus at higher densities to produce the higher emission. As a result, flux ratios of emission lines formed at different temperatures should vary smoothly with increasing emission. Linsky, France, & Ayres (2013) showed that this is indeed the case. The slow increase in the intrinsic flux ratios of Ly-$\alpha$/MgII, Ly-$\alpha$/CII, Ly-$\alpha$/CIV, and even Ly-$\alpha$/X-rays (see Figure 4) with the observed emission fluxes, provides a simple way for estimating the intrinsic Ly-$\alpha$ flux by observing another emission line or X-ray flux at the same time. The flux ratios are well characterized for F, G, and K stars. For the new observations of M dwarfs in the MUSCLES Treasury Survey program (France *et al.* 2016), the Ly-$\alpha$ and other emission lines and the X-ray flux are being observed at the same time to provide accurate flux ratios.

• In the absence of observed Ly-$\alpha$ or any other emission line, Linsky *et al.* (2013) showed that one can still obtain a factor of two estimate of the intrinsic Ly-$\alpha$ line flux from the stellar effective temperature and an indicator of stellar activity, for example, the stellar rotation rate (see Figure 5), provided there is no large flare event.

• In the very few cases when the stellar radial velocity is sufficiently large to Doppler shift the entire stellar emission line outside of the interstellar absorption, the observed Ly-$\alpha$ line is the intrinsic emission from the star. One example of an extremely high radial velocity M dwarf observed by HST is Kapteyn's star ($v_R = +245$ km/s).
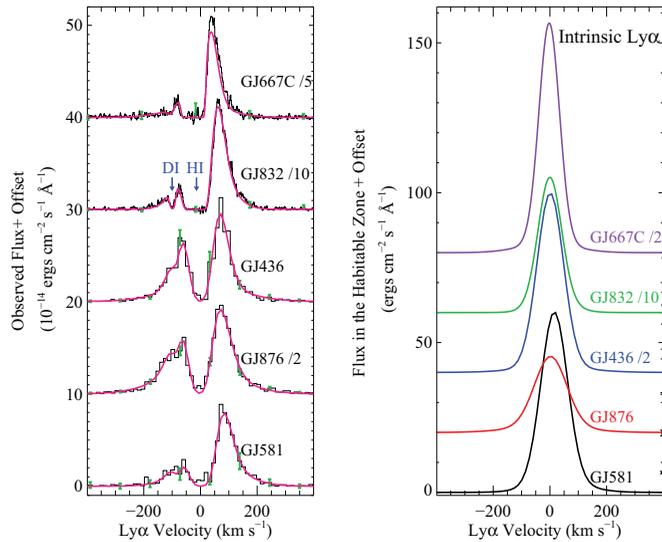
**Figure 3.** *Left:* Ly-$\alpha$ line profiles (black histograms) obtained using the E140M and G140M gratings of the *Space Telescope Imaging Spectrograph (STIS)* on *HST*. The convolution of a two-component Gaussian representing the intrinsic Ly-$\alpha$ emission with interstellar absorption is overplotted in pink. HI and DI blue arrows mark the interstellar Ly-$\alpha$ lines of hydrogen and deuterium. The spectra are scaled and offset by $10^{-14}$ erg cm$^{-2}$ s$^{-1}$. *Right:* The derived intrinsic stellar Ly-$\alpha$ emission lines (with similar offsets) observed at 0.16 AU, the approximate habitable zone for these M stars. Figure from France *et al.* (2013).
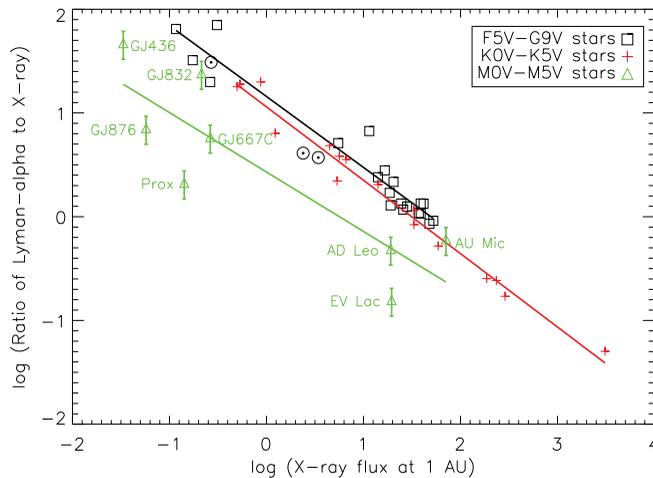


**Figure 4.** Plot of the Ly-$\alpha$/X-ray flux ratio vs. the observed X-ray flux at 1 AU for all stars with known intrinsic Ly-$\alpha$ fluxes. The solid lines are least-squares fits to the data for F9 V–G9 V stars (black), K0 V–K5 V stars (red), and M0 V–M5 V stars (green). Data for the quiet Sun, moderately active Sun, and active Sun are indicated by the dotted circle symbols. The wide scatter for the M dwarfs (identified by name) results for their high variability and observations of Ly-$\alpha$ and X-ray fluxes at different times. Figure from Linsky *et al.* (2013).

## 3. Effects of Host Star Ly-$\alpha$ Emission on Exoplanet Photochemistry

Figure 6 shows the mixing ratios of important molecules and atoms calculated in a photochemistry model for a hypothetical hot Jupiter located at 0.005 AU from the M dwarf star GJ 832. We modeled the planet's atmosphere using a 1D code that includes the
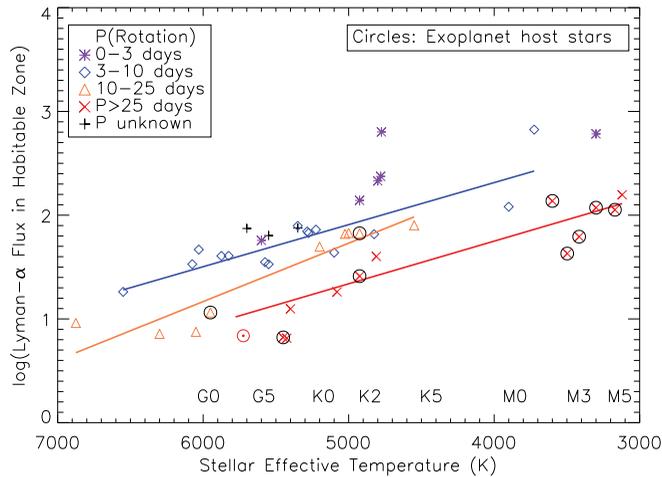
**Figure 5.** The intrinsic stellar Ly-$\alpha$ flux in the habitable zone vs. stellar effective temperature. Symbols indicate host star rotation periods, an indicator of activity. Least-squares linear fits are shown for the stars in different rotation period bins. Stars with known exoplanets are circled and the quiet Sun is indicated by a dotted circle. Note the clear trend of increasing Ly-$\alpha$ flux in the habitable zone with decreasing effective temperature. Figure from Linsky *et al.* (2013).
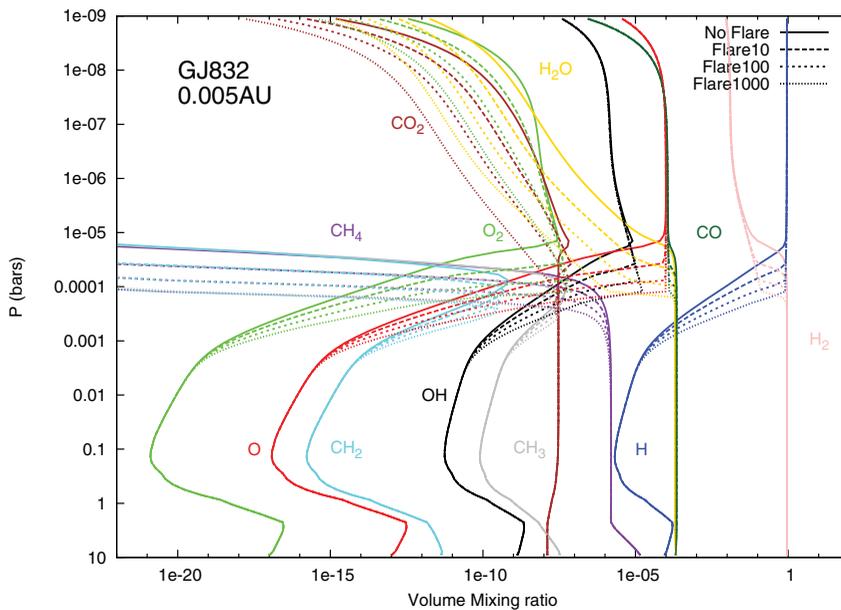


**Figure 6.** Photochemistry in the atmosphere of a hypothetical hot Jupiter located at 0.005 AU from the M dwarf GJ 832. The mixing ratios were computed for the UV flux observed from this weakly active star and for the Ly-$\alpha$ flux multiplied by factors of 10, 100, and 1000 corresponding to flares with increasing flux. Increasing Ly-$\alpha$ flux greatly reduces the mixing ratios of $H_2O$, $CO_2$, and $CH_4$ while increasing the mixing ratios of their photodissociation products (H, O, $O_2$, $CH_2$, and $CH_3$) at atmospheric pressure levels $P < 10^{-3}$ bars.

calculus of thermal structure and chemistry and disequilibrium effects such as molecular diffusion, vertical mixing and photochemistry (Miguel & Kaltenegger 2014; Miguel *et al.* 2015). The four input fluxes are the observed Ly-$\alpha$ and UV flux merged with a synthetic spectrum from the PHOENIX models (Allard *et al.* 2007) and simulations of stellar flares

by increasing the Ly-$\alpha$ flux by factors of 10, 100, and 1000 to explore the effects of extreme differences in Ly-$\alpha$ fluxes on exoplanet atmospheres. Even relatively inactive M dwarf host stars show flare enhancements of order $10 - 50$ (Loyd & France 2014; France *et al.* 2015), and we include enhancements as large a factor of $10^3$ to estimate the potential UV luminosity enhancement during superflare events. Figure 6 shows that photochemistry dominates the chemical reactions at atmospheric pressures less than $10^{-3}$ bars, and that the effect of enhancing the Ly-$\alpha$ flux is to greatly reduce the mixing ratios of $H_2O$, $CO_2$, and $CH_4$ and increase the mixing ratios of their photodissociation products at deeper levels in the atmosphere. Miguel *et al.* (2015) has shown this for the mini-Neptune GJ 436b, and Rugheimer *et al.* (2015) has shown this for super-Earths.

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