

# Lyman- $\alpha$ : The Many Applications and Challenges of This Powerful Emission Line

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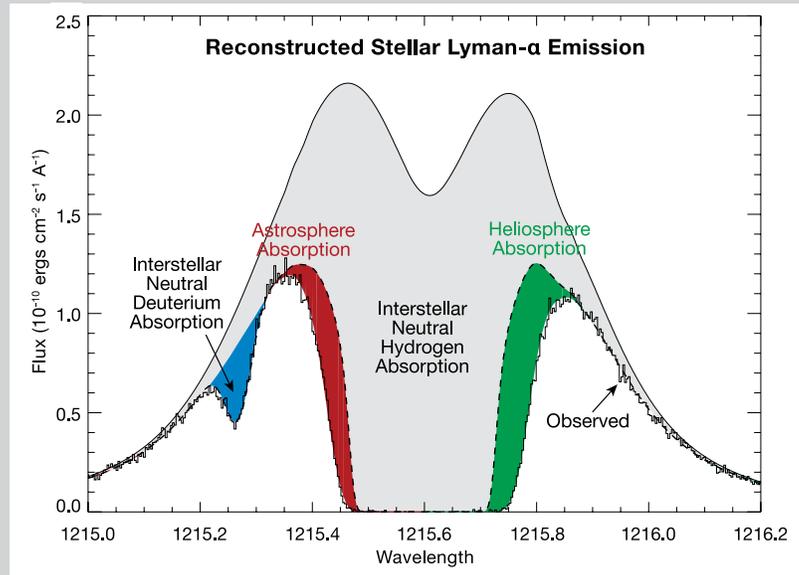
The atomic hydrogen Lyman- $\alpha$  line centered at 1215.67 Å has proven to be extremely valuable for studying stellar mass loss, fluorescent excitation of molecular hydrogen in the environments of very young stars, the deuterium/hydrogen ratio in the Galaxy, and mass loss and photochemical processes in exoplanet atmospheres. These powerful applications result from Lyman- $\alpha$  being the strongest emission line in the ultraviolet spectrum of solar-type stars and as strong as the entire ultraviolet spectrum of cooler stars. The UV-sensitive Space Telescope Imaging Spectrograph and Cosmic Origins Spectrograph on the *Hubble Space Telescope* have been very effective tools for studying these diverse phenomena, despite the challenges posed by Lyman- $\alpha$ 's extreme opacity and the absorption of most of its flux by interstellar hydrogen.

## The anatomy of the Lyman- $\alpha$ line

The observed Lyman- $\alpha$  emission line of the nearby star  $\alpha$  Centauri B shown in Figure 1 highlights the challenges and opportunities for using this spectral line as a probe of stars and interstellar gas. Even though this star is only 4 light-years away, the optical depth at the center of the interstellar absorption exceeds 100,000, and the amount of interstellar absorption in the line center is difficult to analyze. Except for the very few rapidly moving stars like Kapteyn's star (radial velocity 245 km s<sup>-1</sup>), interstellar absorption removes the entire stellar emission-line core, requiring some technique for reconstructing the intrinsic stellar emission line.

Fortunately, the deuterium Lyman- $\alpha$  absorption line is located at -81.55 km s<sup>-1</sup> relative to the hydrogen Lyman- $\alpha$  line. D and H have nearly the same excitation and ionization in the warm interstellar medium, but different thermal broadening and abundance. For many stars located within the low-density interstellar gas extending to roughly 300 light-years from the Sun, known as the Local Cavity, interstellar absorption in the D line is not saturated. As a result, one can infer the interstellar H absorption profile by fitting the D-line profile assuming the present-day cosmic abundance ratio with the heavier singly ionized iron and magnesium ions, providing information on the interstellar velocity dispersion along the line of sight.

Using this technique, Wood et al. (2005a) have reconstructed the Lyman- $\alpha$  emission lines of 40 stars. France et al. (2013) have developed another reconstruction technique useful for lines of sight with simple interstellar gas velocity structures. Even for the nearest stars, the intrinsic stellar flux is at least twice the observed value and often much larger. With these reconstructed Lyman- $\alpha$  fluxes, Linsky et al. (2013) have identified correlations with other stellar emission lines and stellar activity parameters that provide estimates of the intrinsic Lyman- $\alpha$  fluxes of stars like the Sun or cooler, including exoplanet host stars.



**Figure 1:** The Lyman- $\alpha$  line profile of the middle-aged K1 V star  $\alpha$  Centauri B (thick line) observed with the echelle grating (resolution  $\lambda/\Delta\lambda = 90,000$ ) of *Hubble's* first generation instrument, the High Resolution Spectrograph. The unabsorbed Lyman- $\alpha$  emission line emitted by the stellar chromosphere (thin line) has been reconstructed from the deuterium absorption line, the present-day D/H ratio, and kinematic information on the interstellar medium from heavy ions. The light gray shading indicates absorption by interstellar hydrogen, and the blue shading centered at 1215.3 Å (-81.55 km s<sup>-1</sup> from the center of the hydrogen absorption) is absorption by interstellar deuterium. Extra absorption (green) on the long wavelength side of the interstellar hydrogen absorption is produced by hydrogen in the solar hydrogen wall. Extra absorption (red) on the short wavelength side of the interstellar absorption is produced by hydrogen in the stellar hydrogen wall. The original figure is from Linsky & Wood (1996).

## Deuterium in the local Galactic disk

The deuterium Lyman- $\alpha$  line also plays a critical role in measuring the deuterium-to-hydrogen number density ratio (D/H), which is an important test of the density of ordinary matter and the creation of H, D, and He in the very early Universe. Since, the observed D/H ratios in the Galactic disk gas are altered by many competing processes, sorting out these processes requires accurate D/H measurements for a variety of sight lines through different regions of the Galaxy.

For sight lines to the very closest stars, the interstellar D and H Lyman- $\alpha$  lines measure the D/H ratio, but for longer lines of sight in the Galaxy, Lyman- $\beta$  and the higher lines in the Lyman series provide the required range of optical depths in both the D and H lines to accurately measure the D/H ratio. Analysis of these higher Lyman lines along many lines of sight observed with the *Far Ultraviolet Spectrograph Explorer (FUSE)* satellite allowed Linsky et al. (2006) to infer a D/H ratio of  $15.6 \pm 0.4$  parts per million (ppm) in the gas located within about 300 light-years of the Sun.

At further distances, the large range in interstellar gas D/H ratios between 4 and 23 ppm can be explained by different amounts of D gas depletion onto dust grains along these lines of sight. This technique has allowed Cooke et al. (2014) and others to infer D/H ratios in very metal-poor gas toward quasars using the Lyman series lines redshifted into the *Hubble* spectral range.

## Mass loss from solar-like and cooler stars

Unexpectedly, the deuterium Lyman- $\alpha$  interstellar absorption has also provided a critical clue for measuring stellar mass-loss rates, a measurement needed to calculate the erosion of planetary atmospheres.

The slowing down of cool-star rotation rates with age requires that these stars lose mass, but there has been no reliable technique for measuring these mass-loss rates. A critical clue to finding a mass-loss rate diagnostic was provided by the velocity separation between the D and H Lyman- $\alpha$  lines, which is fixed by atomic physics at  $-81.55$  km s $^{-1}$ , but is often significantly different from the predicted value.

The likely cause is charge exchange between outflowing stellar-wind protons and interstellar H atoms that produces a pileup of heated-decelerated H atoms forming a hydrogen wall in the outer heliosphere and in its stellar analog, the astrosphere. As shown in Figure 1, the heliospheric hydrogen wall produces absorption on the long wavelength side of the interstellar H absorption, and the astrospheric hydrogen wall produces absorption on the short wavelength side. Depending on which absorption feature is stronger, the separation of the interstellar D and H absorption-line centers can be either larger or smaller than the atomic physics value.

The breakthrough in finding a useful spectral diagnostic for stellar mass loss occurred when Wood et al. (2005b) showed that the observed Lyman- $\alpha$  profiles are well matched by models of the interaction between stellar winds and the interstellar medium. These models predict that the astrospheric absorption feature moves to shorter wavelengths (more negative velocities) relative to the interstellar H absorption with increasing stellar mass-loss rate. Figure 2 shows an example of using the shape of the astrospheric absorption feature to infer the stellar

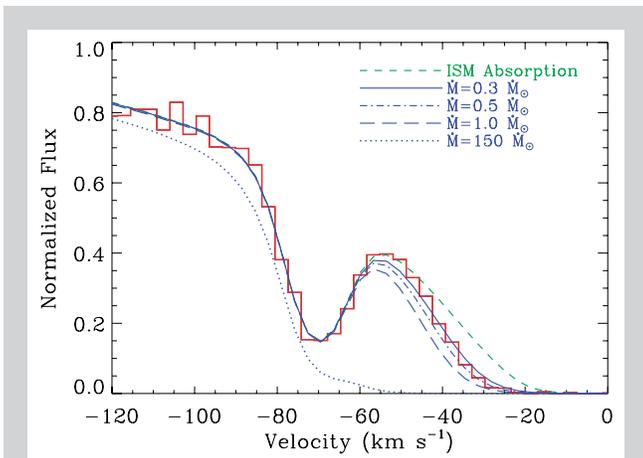
mass-loss rate, in this case for the young, solar-like star  $\pi^1$  Ursa Majoris.

Accurate measurements of the astrospheric Lyman- $\alpha$  absorption require high-resolution spectra observed through a narrow slit to suppress geocoronal emission (solar Lyman- $\alpha$  photons scattered by H atoms in the Earth's outer atmosphere). Only the high-resolution modes of the STIS instrument can obtain the Lyman- $\alpha$  spectra needed to measure cool star mass-loss rates. New observations are needed while STIS is still operating to measure the mass-loss rates of stars that are very active, very cool, and very young.

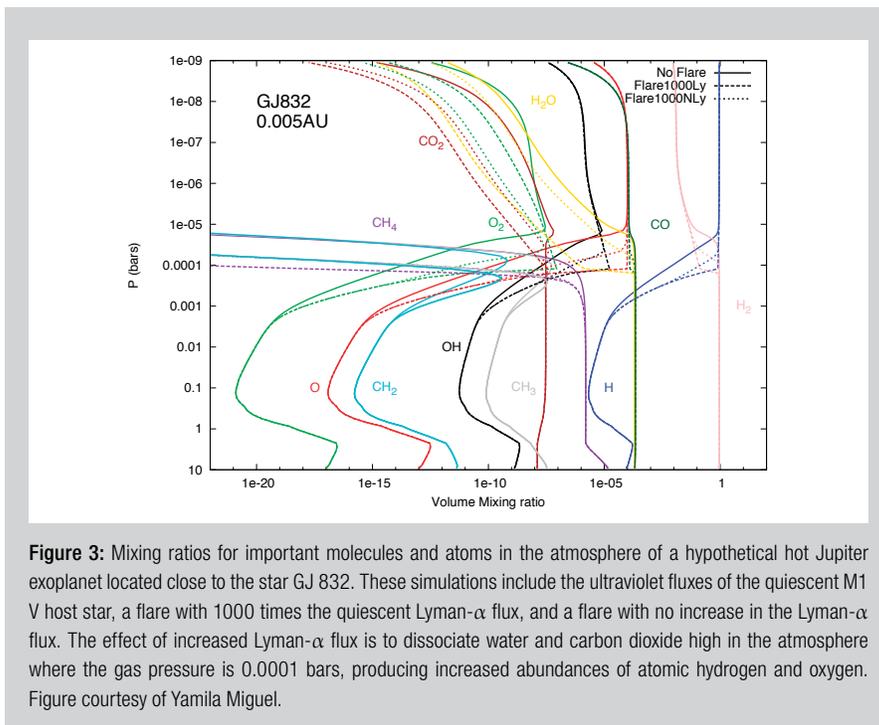
## Fluorescence of H<sub>2</sub> and CO in the circumstellar disks of very young stars

For very young stars with circumstellar disks, generally called classical T Tauri stars (CTTS), reconstructed stellar Lyman- $\alpha$  emission lines are the background light sources that pump the rich cluster of fluorescent H<sub>2</sub> emission lines in their ultraviolet spectra. These fluorescent processes provide a unique tracer of small amounts of residual gas near the surfaces of protoplanetary disks left behind during planetary formation. Herczeg et al. (2004) found that for TW Hya, a prototypical CTTS, the fluorescing H<sub>2</sub> gas is located in a circumstellar disk at temperatures near 2500 K.

There are also UV emission lines of CO seen in *Hubble* COS spectra that are pumped by Lyman- $\alpha$  in CTTS (France et al. 2011). The *Hubble* Cycle 17 large observing program "The Disks, Accretion, and Outflows (DAO) of T Tau Stars" (P.I. Gregory Herczeg) has provided a wealth of observations of these stars, including many examples of Lyman- $\alpha$  fluorescence.



**Figure 2:** A portion of the Lyman- $\alpha$  line of  $\pi^1$  UMa, a rapidly rotating young G1.5 V star, observed with the Space Telescope Imaging Spectrograph's E140M grating (resolution  $\lambda/\Delta\lambda = 45,000$ ). The observed profile (red) is compared with astrospheric models with different mass-loss rates in units of the solar mass-loss rate ( $2 \times 10^{-14} M_{\odot}/\text{yr}$ ). Increasing mass-loss rate extends the astrospheric absorption to more negative velocities. Figure from Wood et al. (2014).



**Figure 3:** Mixing ratios for important molecules and atoms in the atmosphere of a hypothetical hot Jupiter exoplanet located close to the star GJ 832. These simulations include the ultraviolet fluxes of the quiescent M1 V host star, a flare with 1000 times the quiescent Lyman- $\alpha$  flux, and a flare with no increase in the Lyman- $\alpha$  flux. The effect of increased Lyman- $\alpha$  flux is to dissociate water and carbon dioxide high in the atmosphere where the gas pressure is 0.0001 bars, producing increased abundances of atomic hydrogen and oxygen. Figure courtesy of Yamila Miguel.

### Hot exoplanets with Lyman- $\alpha$ tails

Reconstructed stellar Lyman- $\alpha$  emission lines are also the background light sources for studying exoplanet atmospheres during transits. The discovery of significantly more Lyman- $\alpha$  line absorption during the transit of the exoplanet HD 209458b compared to STIS observations outside of transit led Vidal-Madjar et al. (2003) to conclude that this hot-Jupiter exoplanet is losing mass.

Subsequent observations by this group and others (see the recent review by Fossati 2015) showed that other gas giant exoplanets are also losing H and other elements from their outer atmospheres through hydrodynamic outflows (also known as hydrodynamic “blow-off”), ion pickup by the stellar wind, and Roche lobe overflow (Bourrier & Lecavelier des Etangs 2013). Absorption seen in H Lyman- $\alpha$  and other lines after transit egress (e.g., Kulow et al. 2014) indicates planetary mass loss in a comet-like tail, and absorption seen prior to ingress has been interpreted as absorption by a shock ahead of the planet in its orbit.

### Photochemistry in exoplanet atmospheres

Finally, reconstructed stellar Lyman- $\alpha$  emission lines also control the photochemistry in exoplanet atmospheres. The peak photodissociation cross-sections of water, carbon dioxide, and methane are located in the 1000–1700 Å spectral region. Since the stellar Lyman- $\alpha$  emission line is the strongest emission feature in the UV spectra of G and K stars and is as strong as the entire 1200–3200 Å region in M dwarfs (France et al. 2013), Lyman- $\alpha$  plays a critical role in the photochemistry of these molecules.

Figure 3 shows a simulation of the effects of Lyman- $\alpha$  radiation on several molecular species in the atmosphere of a hypothetical hot Jupiter located close to its cool host star. In this simulation and in simulations for the mini-Neptune GJ 436b (Miguel et al. 2015), an increase in the Lyman- $\alpha$  flux by a factor of 1000, as could occur during a flare or continuously in very active stars, reduces the H<sub>2</sub>O and CO<sub>2</sub> mixing ratios by factors of 10–100 at atmospheric levels above 0.0001 bars.

At the same time, the mixing ratios of atomic H and O and O<sub>2</sub> are increased by the same factors between pressure levels 0.0001 and 0.00001 bars. This simulation demonstrates that O, O<sub>2</sub>, and O<sub>3</sub> can be produced abiotically (e.g., Domagal-Goldman et al. 2014; Tian et al. 2014). Also, the production of atomic H and O by Lyman- $\alpha$  photodissociation of H<sub>2</sub>O and their ionization by extreme-ultraviolet radiation from the host star can lead to mass loss by ion pickup in the stellar wind. This process may explain the loss of the atmosphere of Mars (Brain et al. 2009).

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