

The Lyman line series and stellar, exoplanet, interstellar, and deuterium astronomy with ARCUS

Jeffrey Linsky

JILA/University of Colorado, Boulder CO USA

ARCUS Community Science Meeting

May 4-5, 2023

These capabilities of ARCUS are needed and unique for stellar, exoplanetary, and ISM studies

- X-ray spectroscopy (10-60 Å) with $R \approx 3500$.
- FUV spectroscopy (970-1350 Å) with $R=22,000$ (13.6 km/s) and 6 times higher sensitivity than FUSE.
- Both capabilities are simultaneous and **uniquely** important for studying variable sources.
- 7 day period high Earth orbit supports long duration uninterrupted observations with low geocoronal emission.

The ability to observe spectra of several Lyman lines from nearby targets is unique

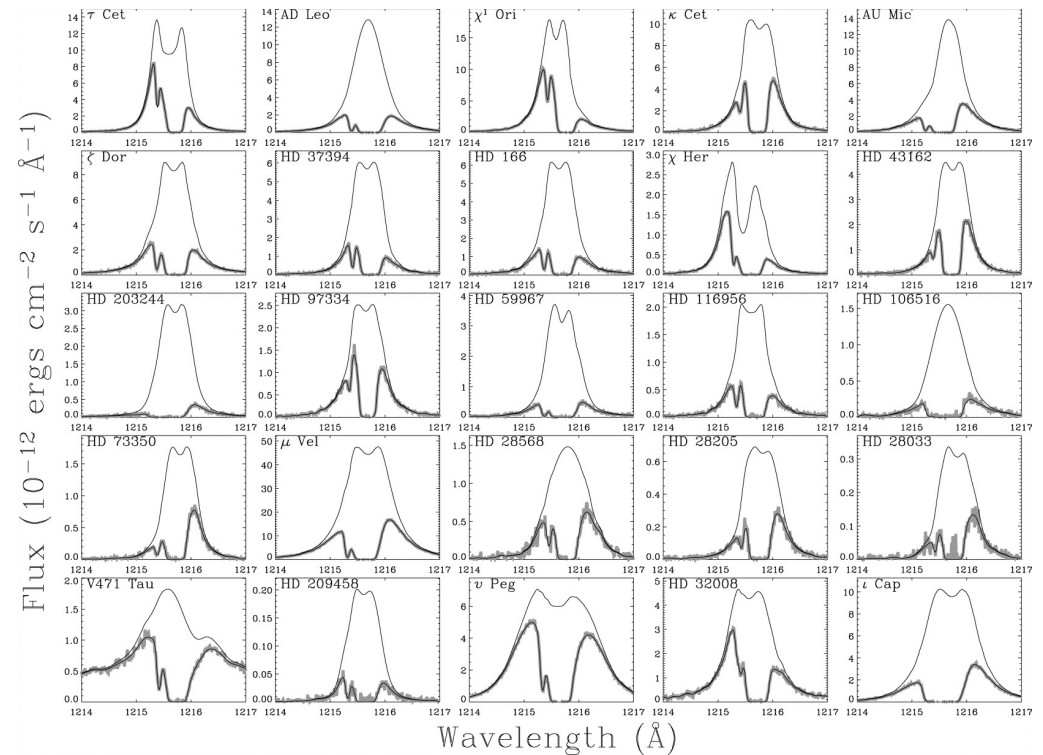
- HST could only observe Lyman- α and FUSE could only observe the higher lines with low sensitivity.
- ARCUS FUV resolution is 14 km/s.
- D and H Lyman lines separated by 81 km/s are resolved by ARCUS FUV spectrograph.
- $D/H \approx 1.5 \times 10^{-5}$ in the local ISM, so a broad range of optical depths is available by observing 2 or even 3 H and D Lyman lines.
- HEO greatly suppresses geocoronal Lyman- α foreground emission

H and D Lyman line center optical depths for $\log N(\text{HI})=18.5$

Line	$\lambda(\text{nm})$	f	$\tau(\text{H})$	$\tau(\text{D})$
Lyman- α	121.67	0.4162	60,000	0.9
Lyman- β	102.57	0.0791	11,800	0.17
Lyman- γ	97.25	0.02899	4,200	0.06
Lyman- δ	94.97	0.01394	2,040	0.021

Importance of the Lyman lines for interstellar astronomy

- The local ISM within 15 pc includes many partially ionized clouds identified by velocity vectors.
- The clouds are measured by interstellar N(HI) along many sightlines to stars.
- Inference of N(HI) involves reconstructing the **intrinsic** Lyman emission line using information from the D and MgII lines.
- Since H Lyman- α is very optically thick, reconstructing the higher Lyman lines would be very helpful.

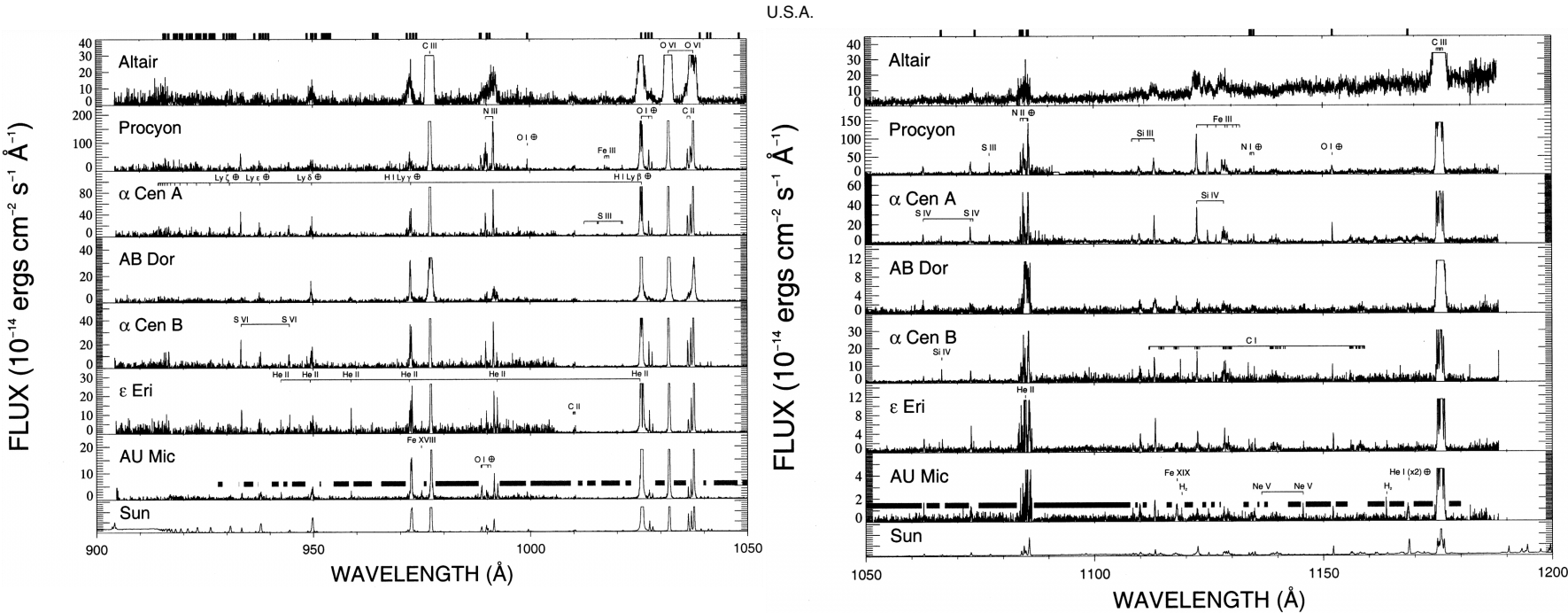


Wood et al. ApJS 159, 118 (2005)

Importance of the Lyman lines for the study of stellar activity and transients

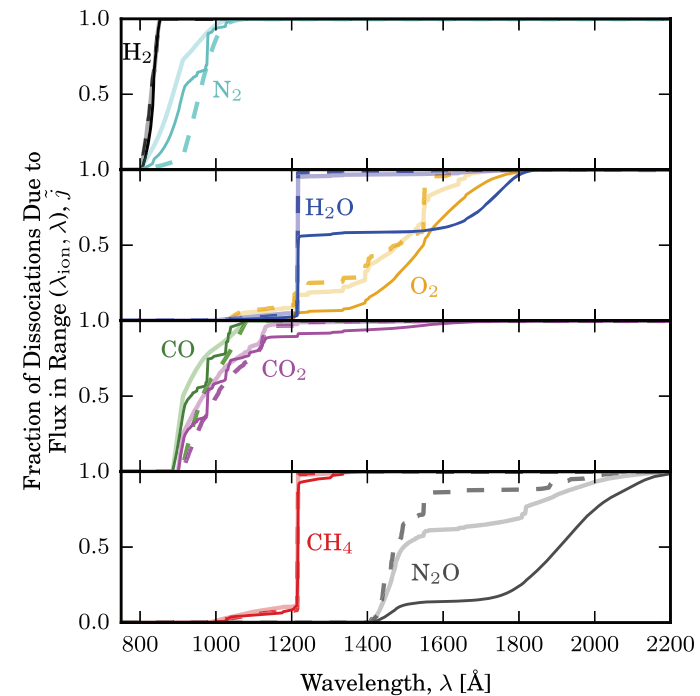
- Lyman- α is the brightest emission line for G stars and as bright as all other emission lines for M stars. Measuring the **intrinsic** Lyman- α flux is essential for estimating the total FUV stellar emission.
- ISM absorption makes it difficult to measure the **intrinsic** Lyman- α emission. The D line helps.
- Analysis of the Lyman- α and Lyman- β lines together would be a great test because very different interstellar absorption.
- Simultaneous X-ray and FUV spectroscopy will supply unique data for studying stellar flares, coronal mass ejections, and activity indicators. See talks by Osten and Shkolnik. This is mostly GO science.
- Previous studies required difficult coordination and scheduling between several spacecraft.
- The ARCUS FUV spectrograph will include 97-120 nm lines of C II, C III, Si III, He II, O VI, Fe XVIII, and Fe XIX in addition to the 120-158 nm emission lines studied by HST.

FUSE spectra of cool stars (Redfield et al. 2002)



Importance of the Lyman lines for exoplanet atmospheres and mass loss

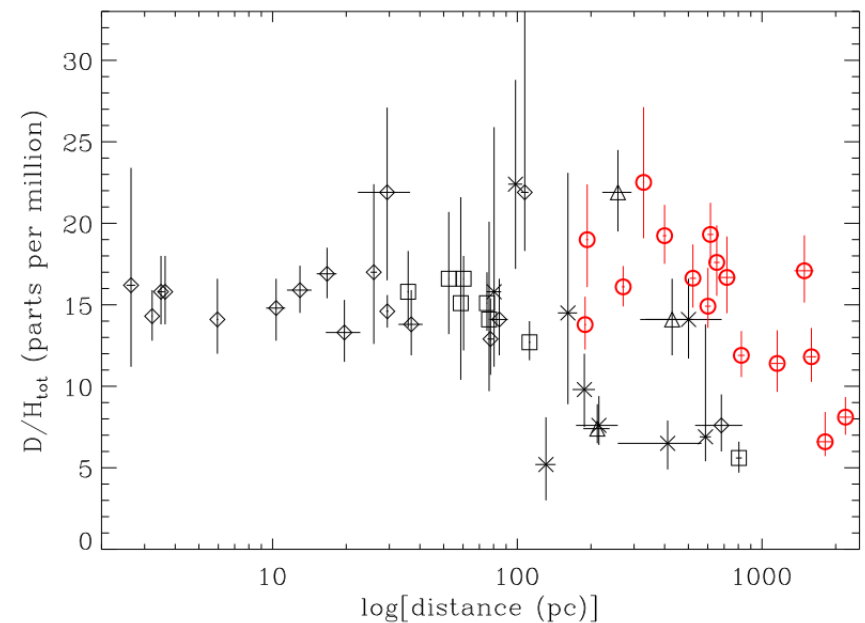
- Stellar Lyman- α emission photo-dissociates H₂O and CH₄ in exoplanet atmospheres.
- Stellar emission below 120 nm photo-dissociates CO₂, CO, H₂ and N₂ in exoplanet atmospheres.
- Exoplanet mass loss can be observed by Lyman- α and other lines during transits. Low geocoronal emission is important.



Lloyd et al. ApJ 824, 102 (2016). For ϵ Eri, GJ 581, and Sun

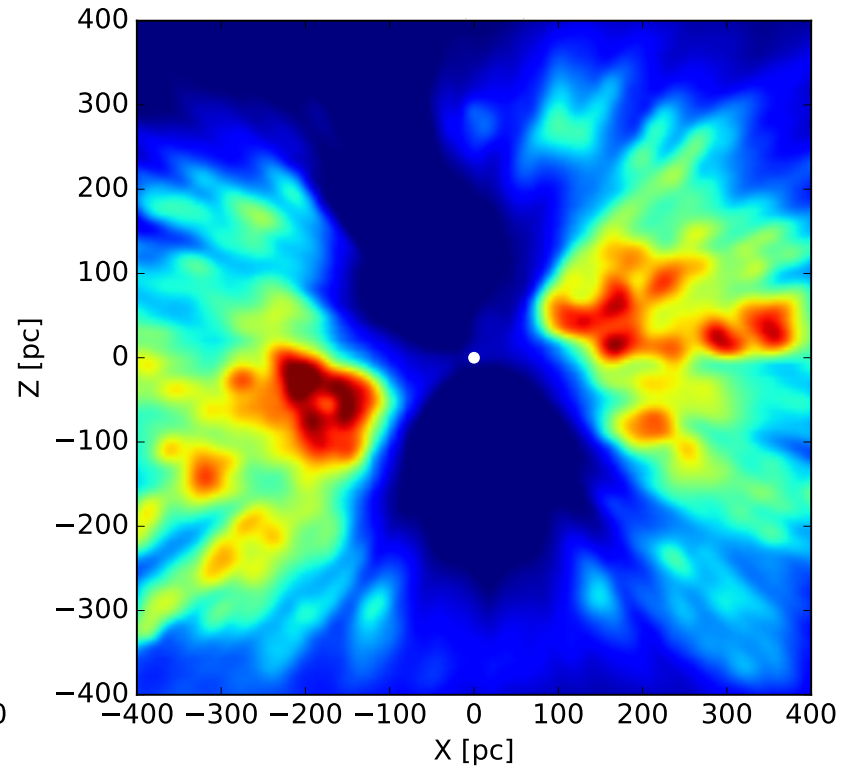
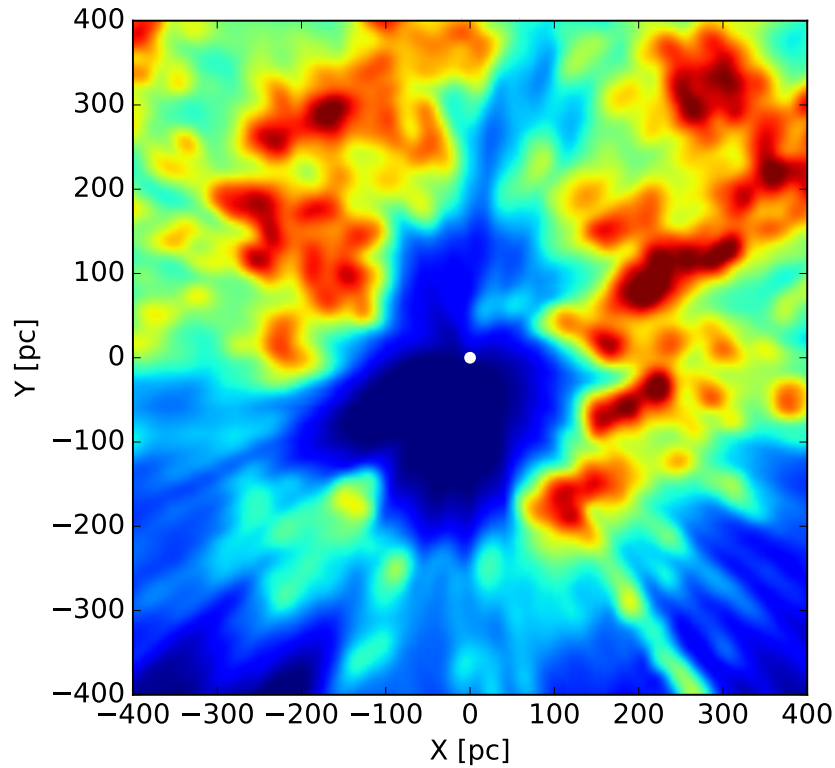
Importance of the Lyman lines for Galactic chemical evolution using D/H as a test

- The D/H ratio in the gas phase varies in the Galaxy due to astration, removal of D from gas phase on to grains, patchy infall of near-primordial gas, and incomplete mixing.
- D/H ratios for most sightlines within the Local Bubble (100-200 pc) are based only on Lyman- α .
- Main uncertainty is N(HI). Simultaneous analysis of both Lyman- α and Lyman- β would test previous studies.



Friedman et al. ApJ 946, 34 (2023)

Local Cavity (Bubble) as determined from dust absorption (blue is low dust and red is high dust). Views from above and from the Galactic plane. (Pelgrimes et al. A+A 636, A17 (2020))



Conclusions

- The combination of X-ray and FUV spectroscopy will make ARCUS a major contributor to our understanding of stellar activity and transients, exoplanet atmospheres, interstellar medium, D/H and Galactic chemical evolution.
- Analysis of the fluxes and spectral shapes of the Lyman- α , Lyman- β , and Lyman- γ lines (with much higher sensitivity than FUSE) will play critical roles in each of these topics.
- The 7 day orbit of ARCUS is essential for minimizing geocoronal emission and providing long uninterrupted observing programs.
- The ARCUS development team (specifically Kevin France) should provide the highest feasible spectral resolution, throughput, and line profile shapes for the Lyman and other lines in the FUV.

Any questions ?