UV-Driven Evolution and Chemistry of Protoplanetary Disks: Insights from *HST*'s ULLYSES Program

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Motivation

Accreting T Tauri stars generate strong UV radiation fields, which regulate gas-phase chemistry in protoplanetary disks and establish the inventories of volatile-bearing molecules. However, there has previously been little overlap between the population of disks with available UV spectroscopy and those with sub-mm and/or infrared observations of molecular gas, limiting statistical studies of how UV radiation fields impact the physical and chemical structure of disks while accretion is ongoing.

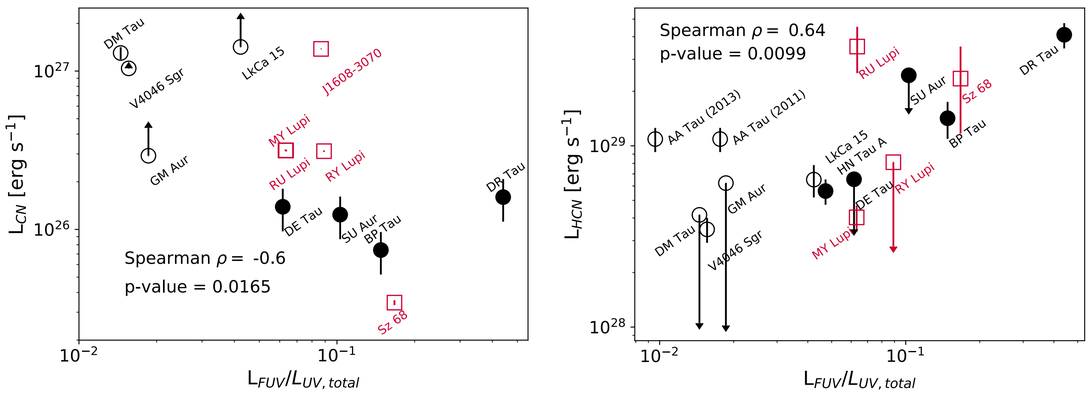
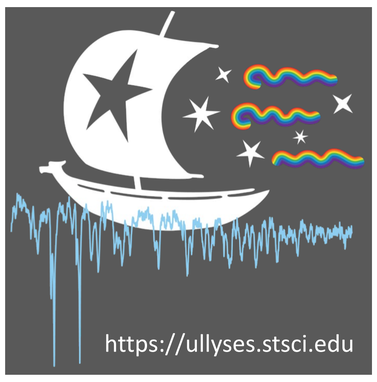


Fig. 1: At face value, targets with stronger FUV radiation fields show weaker sub-mm CN emission (left) and stronger IR HCN (right). However, the small sample size makes it difficult to observationally isolate the impact of UV irradiation on the underlying abundances from other factors (e.g., C/O, disk temperature structure; Arulanantham+ 2020).

Targets and Observations

The sample of T Tauri stars with uniform UV spectroscopy from HST recently expanded to *N* = 112, through the Ultraviolet Legacy Library of Young Stars as Essential Standards (ULLYSES) Director's Discretionary program (Roman-Duval+ 2020). The spectra include Lyα emission, which contributes ~88% of the total UV flux (France+ 2014), on average, after undergoing millions of scattering events within the protostellar environment. This allows the radiation to penetrate deeper into the gas layer than continuum photons (see e.g., Bergin+ 2003, Bethell & Bergin 2011). Fluorescent H_2 emission lines are also detected, from molecules that are pumped into excited electronic transitions by Lyα photons (see e.g., Herczeg+ 2002, France+ 2012, Hoadley+ 2015).



Results: Linking Lyα Emission to Protoplanetary Disk Observations

We find that the shapes of the Lyα emission lines from T Tauri stars, parametrized by the ratios of red (λ > 1215.67 Angstroms) to blue (λ < 1215.67 Angstroms) flux, are correlated with the infrared spectral indices and occurence rates of high-velocity forbidden emission line components (Arulanantham+ 2021). We also find that the H I velocities derived from simple shell scattering models are statistically significantly correlated with the shapes of the Lyα profiles and *K*-band veiling, indicating that the turnover in Lyα profile shape occurs as excess emission from T = 2000 K dust disappears, although the dust clearing mechanisms are difficult to constrain without high-resolution images of the infrared and sub-mm continuum (Arulanantham+ 2023). Together these results imply that the UV radiation fields and protoplanetary disks evolve in unison throughout the process of planet formation.

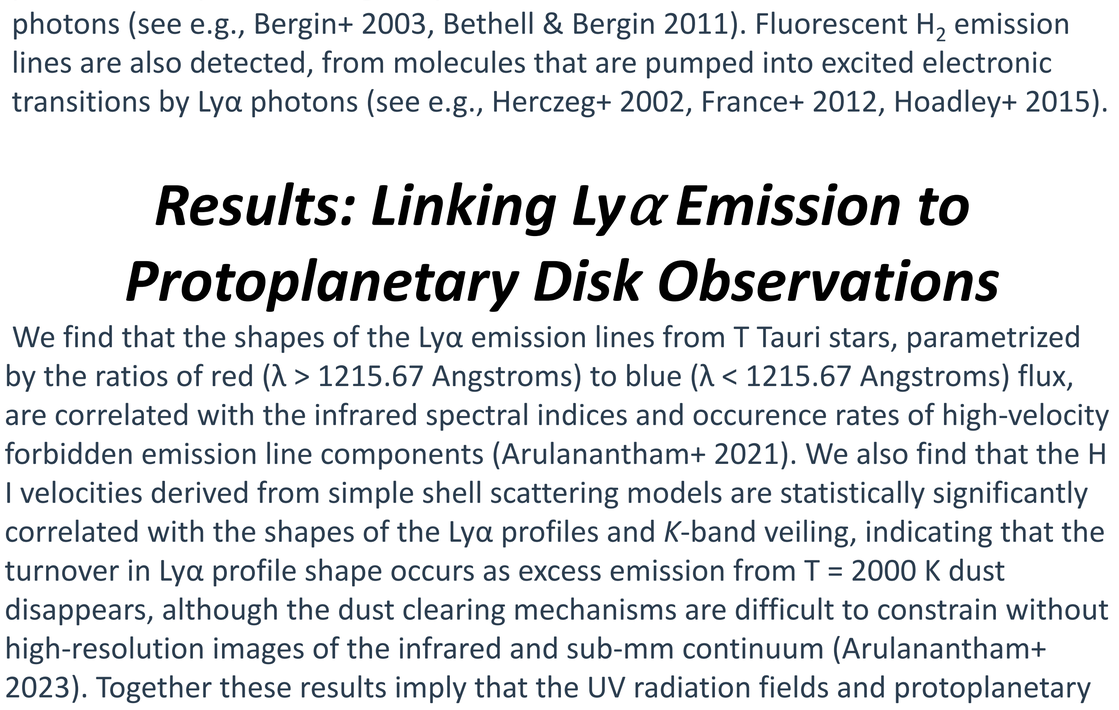


Fig. 2: Illustration of characteristic Lyα emission line shapes and corresponding stages of protoplanetary disk evolution (Arulanantham+ 2023). The turnover from P Cygni-like to inverse P Cygni-like Lyα profile indicates that there is significant evolution in UV irradiation of molecular gas over the disk lifetimes.

Results: Constraining Disk Vertical Structure

The dominant formation pathway for CN molecules in protoplanetary disks requires a population of vibrationally excited H_2 (H_2*), at temperatures consistent with surface layers of the disks (T = 2000 K; Visser+ 2018, Cazzoletti+ 2018). The population of H_2* at r < 10 au can absorb Lyα photons, producing fluorescent emission lines observed in the ULLYSES spectra from *HST* (France+ in prep). We use a grid of DALI models (Bruderer+ 2012) to explore whether the UV-fluorescent H_2 emission lines can help untangle degeneracies between disk flaring, UV irradiation, and disk mass. The distributions of H_2* from the models are input to a Lyα radiative transfer code (Hoadley+ 2015) to fit the observed UV spectra from RY Lupi and MY Lupi (Arulanantham+, in prep).

	RY Lup	MY Lup
UV Luminosity	4.94e30 erg/s	3.5e29 erg/s
CN Luminosity	2.2e25 erg/s	2.3e25 erg/s
References	Langlois+ 2018, Arulanantham+ 2018, van Terwisga+ 2019	Avenhaus+ 2018, Arulanantham+ 2020, van Terwisga+ 2019

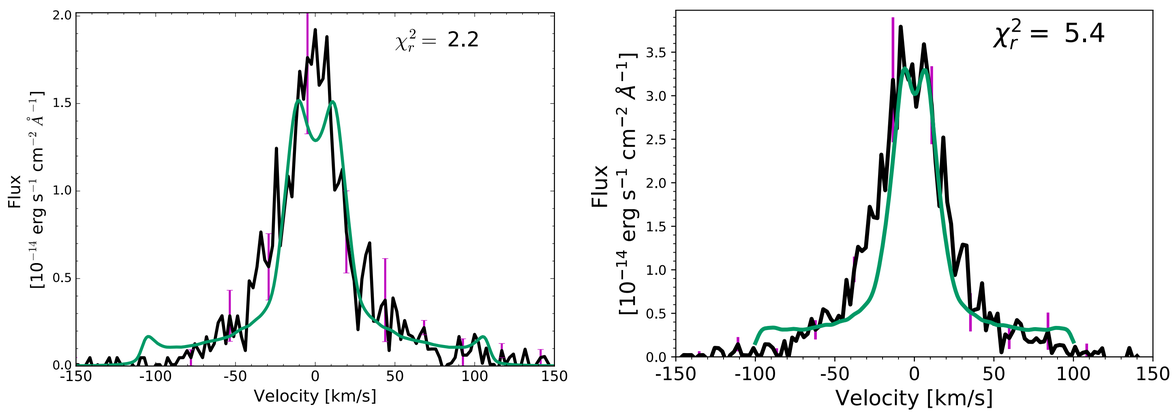


Fig. 3: UV-fluorescent H_2 emission (black) and best-fit DALI models (green) for MY Lup (left) and RY Lup (right; Arulanantham+ in prep). The spectrum from MY Lup is well fit by a flared disk model with large gas mass (0.1 $M_\odot$) and low UV luminosity (0.015 $L_\odot$). The spectrum from RY Lup is also well fit by a flared disk model but requires a lower gas mass (0.001 $M_\odot$) and higher UV luminosity (0.15 $L_\odot$), consistent with observations of both systems. A two sample Welch's *t*-test confirms that the two datasets cannot be reproduced by the same model (t = 6.9; p = 10^{-10}).

Conclusions: Implications for Physical-Chemical Disk Models

Multi-wavelength synergies are now possible with UV spectra from ULLYSES and IR and sub-mm observations of molecular gas. ***Together, these datasets may be used to more accurately construct physical-chemical models of protoplanetary disks, providing updated chemical inventories for models of planet formation.*** We do not find a statistically significant relationship between total observed Lyα flux and stellar mass in this sample of K and M-type YSOs, indicating that the expected relationship between disk temperature structure and host star spectral type is more complex than a linear trend and perhaps reflects the scatter in the relationship between stellar mass and accretion rate (see e.g., PPVII Chapter 15). Some of these degeneracies may be untangled by using UV-fluorescent H_2 emission lines to anchor models of UV-sensitive molecules like CN, HCN, and C_2H.

Future Work & Acknowledgements

We are reconstructing the Lyα emission reaching warm molecular gas in the inner disks of ULLYSES targets, to explore how photodissociation rates might change over the disk lifetimes (Arulanantham, Ortiz-Quintana+ in prep)

We are also exploring Lyα propagation through the disk winds, which may enhance UV irradiation of gas at large radii (Chang, Arulanantham+, in prep). This modeling framework is presented in Chang+ 2022, where it was developed for studies of AGN and star-forming galaxies.

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