FUMES. II. Lyα Reconstructions of Young, Active M Dwarfs

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Received 2020 July 1; revised 2021 February 8; accepted 2021 February 9; published 2021 April 23

Abstract

The H I Lyα (1215.67 Å) emission line dominates the far-UV spectra of M dwarf stars, but strong absorption from neutral hydrogen in the interstellar medium makes observing Lyα challenging even for the closest stars. As part of the Far-Ultraviolet M-dwarf Evolution Survey, the Hubble Space Telescope has observed 10 early-to-mid M dwarfs with ages ranging from ~24 Myr to several Gyr in order to evaluate how the incident UV radiation evolves through the lifetime of exoplanetary systems. We reconstruct the intrinsic Lyα profiles from STIS G140L and E140M spectra, and achieve reconstructed fluxes with 1σ uncertainties ranging from 5% to a factor of two for the low-resolution spectra (G140L) and 3%–20% for the high-resolution spectra (E140M). We observe broad, 500–1000 km s⁻¹ wings of the Lyα line profile, and analyze how the line width depends on stellar properties. We find that stellar effective temperature and surface gravity are the dominant factors influencing the line width with little impact from the star’s magnetic activity level, and that the surface flux density of the Lyα wings may be used to estimate the chromospheric electron density. The Lyα reconstructions on the G140L spectra are the first attempted on ∆λ/λ ∼ 1000 data. We find that the reconstruction precision is not correlated with the signal-to-noise ratio of the observation—rather, it depends on the intrinsic broadness of the stellar Lyα line. Young, low-gravity stars have the broadest lines and therefore provide more information at low spectral resolution to the fit to break degeneracies among model parameters.

Unified Astronomy Thesaurus concepts: M stars (985); Interstellar absorption (831); Stellar activity (1580); Stellar chromospheres (230); Ultraviolet astronomy (1736)

Supporting material: figure sets

1. Introduction

Far-ultraviolet (FUV) photons (912–1700 Å) drive photochemistry and heating in planetary upper atmospheres due to the large, wavelength-dependent absorption cross sections of molecules throughout the FUV (e.g., Segura et al. 2005; Loyd et al. 2016). Using the Hubble Space Telescope (HST), the Far-Ultraviolet M-dwarf Evolution Survey (FUMES; HST-GO-14640) has measured the FUV spectral energy distributions of early- to mid-M dwarfs ranging in age from 24 Myr to field age (~5 Gyr), in order to determine how stellar magnetic activity evolves with age as well as to better inform exoplanet atmosphere evolution studies (Pineda et al. 2021). In particular, a large ratio of incident FUV to near-ultraviolet (NUV; 1700–3200 Å) flux on a planet can lead to the abiotic production of oxygen and ozone, which are possible biosignatures (see reviews by Meadows et al. (2018) and Schwieterman et al. (2018)). M dwarfs have intrinsically faint FUV and NUV emission from their cool photospheres, but high levels of magnetic heating (e.g., nonradiative heating) make bright chromospheric and transition region emission lines that raise the FUV/NUV flux ratio two to three orders of magnitude higher than for solar-type stars.

H I Lyα (1215.67 Å) is the brightest M dwarf emission line in the UV (France et al. 2013), and is therefore required for a thorough accounting of the stellar UV energy budget. However, neutral hydrogen gas in the ISM completely attenuates the inner ~80–100 km s⁻¹ of the Lyα line core for even the closest stars. To determine the intrinsic stellar emission, the Lyα line must be reconstructed from the observed wings. Historically, this has been done at high spectral resolving power (λ/∆λ > 40,000) so that the D1 absorption line (~82 km s⁻¹ from H I) can be resolved from the H I absorption line (e.g., Wood et al. 2005). Resolving the optically thin D1 line places strong constraints on the properties of the highly optically thick H I line: column density, radial velocity, and Doppler broadening. France et al. (2013) showed that reliable reconstructions can be performed at lower resolving power (λ/∆λ ∼ 10,000). For the first time, we present reconstructions at an even lower spectral resolving power (λ/∆λ ∼1000), where the H I absorption trough is completely unresolved.

The higher sensitivity of the G140L spectra, as compared to higher-resolution STIS gratings (G140M, E140M, and E140H), eases the detection of the important Lyα line, expanding the volume of M dwarfs for which Lyα emission can potentially be studied. Higher sensitivity also allows for the measurement of very broad Lyα wings (~500–1000 km s⁻¹), which have been known for the Sun (Morton & Widing 1961) and for M dwarfs (Gayley 1994; Youngblood et al. 2016). The broad wings are the result of partial frequency redistribution, which occurs because Lyα is a highly optically thick resonance line (Milkey & Mihalas 1973; Basri et al. 1979). Photons from the lower-opacity, lower-transition region escape in the line core, whereas photons from the higher-opacity chromosphere must diffuse out into the broad wings to escape. Matching the observed wing strength of emission lines like Lyα is a notoriously difficult problem for stellar models, especially for M dwarf models (see Fontenla et al. 2016; Peacock et al. 2019a; Tilipman et al. 2021). More detailed observational constraints support the upcoming generation of stellar models that include chromospheres and transition regions (Peacock et al. 2019b; Tilipman et al. 2021).
The intensity of the chromospheric emission line wings compared to the line core is controlled primarily by the pressure scale height (Ayres 1979), with an inverse dependence on surface gravity. For main-sequence stars, this means that more massive stars have brighter wings, as shown by Wilson & Bappu (1957) for Ca II H&K. However, there is likely a small dependence on magnetic activity (Ayres 1979; Gayley 1994), with more active stars exhibiting stronger wings. Combining the young, active M-dwarf sample of FUMES, two well-known active M dwarfs from the literature (Proxima Centauri and AU Mic), and the more inactive M-dwarf sample from the MUSCLES Treasury Survey (France et al. 2016; Loyd et al. 2016; Youngblood et al. 2016), we address the magnitude of magnetic activity’s effect on the observed Lyα wing strength of M-dwarf stars.

In Section 2, we briefly describe the FUMES observations and reductions, and in Section 3, we thoroughly describe the Lyα reconstructions. These results are used in the main FUMES analysis (Pineda et al. 2021). In Section 4, we analyze the broad Lyα wings and the implications for understanding M-dwarf atmospheres. In Section 5, we summarize our findings.

### 2. Observations and Reductions

Using the STIS spectrograph on board HST, we observed 10 M dwarfs as part of the The Far-Ultraviolet M-dwarf Evolution Survey (FUMES) survey (GO 14640; PI: J. S. Pineda). Properties of the targets are listed in Table 1 and discussed in more detail in Paper I (Pineda et al. 2021). Two of the targets, LP 55-41 and G 249-11, were detected at low signal-to-noise ratios (S/Ns), and we do not attempt Lyα reconstructions for them. Custom reductions were performed using stistools\(^5\) following Loyd et al. 2016, including the exclusion of flares from the extracted spectra of GJ 4334, GJ 410, and HIP 17695. See Pineda et al. (2021) for more details.

### 3. Lyα Reconstructions

#### 3.1. The Model

Our model is comprised of two components: the stellar emission component and the ISM absorption component. We tested different functions for the intrinsic stellar emission, including multiple, superimposed Gaussians, and found that a Voigt profile in emission fits both the line core and the broad wings best. We use the astropy Voigt1D function, which is based on the computation from McLean et al. (1994).

We assume no self-reversal, because past results have shown that the Lyα self-reversal of M dwarfs is small (Wood et al. 2005; Guinan et al. 2016), if present at all (Youngblood et al. 2016; Bourrier et al. 2017; Schneider et al. 2019). Given that the Lyα line center, the region in the spectrum where the self-reversal appears, is usually entirely hidden by the ISM and not well-constrained by the reconstruction, we assume no self-reversal is present. The Voigt emission line model component has four free parameters:

\[
F^\lambda_{\text{emission}} = \mathcal{V}(\lambda, V_{\text{radial}}, A, \text{FWHM}_L, \text{FWHM}_G),
\]

where \(V_{\text{radial}}\) is the radial velocity of the emission line (km s\(^{-1}\)), \(A\) is the Lorentzian amplitude (erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\)); note that we parameterize it in all tables as \(\log_{10} A\), and \(\text{FWHM}_L\) and \(\text{FWHM}_G\) (km s\(^{-1}\)) are the full width at half maximum values for the Lorentzian and Gaussian components, respectively. For use with Voigt1D, \(V_{\text{radial}}\), \(\text{FWHM}_L\), and \(\text{FWHM}_G\) are converted to Å. For the reconstructions on the E140M spectra where Lyα and Si III are not blended, Equation (1) is used, but for the G140L spectra where the two lines are blended, Equation (2) is used:

\[
F^\lambda_{\text{emission}} = F^\lambda_{\text{emission, H I}} + F^\lambda_{\text{emission, Si III}}.
\]

We assume a single ISM absorbing cloud, as such low-resolution spectra (300 km s\(^{-1}\)) are not able to distinguish between ~20–40 km s\(^{-1}\) separated clouds. Youngblood et al. (2016) demonstrated that assuming a single-velocity ISM does not significantly impact the reconstructed Lyα flux. For the ISM component (used for Lyα only), we model the H I and D I absorption lines each as Voigt profiles with linked parameters, using the code lyapy\(^6\) (Youngblood et al. 2016):

\[
F^\lambda_{\text{absorption}} = \mathcal{V}(\lambda, V_{\text{HI}}, \log_{10} N(\text{H I}), b_{\text{HI}}) \times \mathcal{V}(\lambda, V_{\text{DI}}, \log_{10} N(\text{D I}), b_{\text{DI}}),
\]

where \(V_{\text{HI}}\) is the radial velocity (km s\(^{-1}\)) and is assumed to be the same for both H I (1215.67 Å) and D I (1215.34 Å) (\(V_{\text{HI}} = V_{\text{DI}}\), so \(V_{\text{HI}}\) is the reported parameter). Here, \(\log_{10} N\) is the logarithm of the column density (cm\(^{-2}\)), where \(N(\text{H I})\) and \(N(\text{D I})\) are linked.

#### Table 1

| Name         | Other Name | Spectral Type | \(d\) (pc) | \(P_{\text{ex}}\) (day) | \(M\) (M\(_{\odot}\)) | \(R\) (R\(_{\odot}\)) | \(T_{\text{eff}}\) (K) | Age | STIS   | Grating |
|--------------|------------|---------------|------------|--------------------------|-----------------------|-----------------------|------------------------|-----|--------|---------|
| G 249-11     | M4         |               | 29.14      | 52.8\(^a\)               | 0.24                  | 0.26                  | 3277                   | field\(^e\)          | G140L  |
| HIP 112312   | WW PsA     | M4.5          | 20.86      | 2.4\(^a\)                | 0.25                  | 0.69                  | 3173                   | 24 Myr\(^f\)         | E140M  |
| GJ 4334      | FZ And     | M5            | 25.33      | 23.5\(^a\)               | 0.29                  | 0.31                  | 3260                   | field\(^e\)          | G140L  |
| LP 55-41     | M3         |               | 37.04      | 53.4\(^a\)               | 0.41                  | 0.42                  | 3412                   | 650 Myr\(^b\)        | G140L  |
| HIP 17695    | M4         |               | 16.8       | 3.9\(^b\)                | 0.54                  | 0.50                  | 3393                   | 150 Myr\(^f\)        | E140M  |
| LP 247-13    | M3.5       |               | 35.04      | 1.3 \(^c\)               | 0.50                  | 0.49                  | 3511                   | 650 Myr\(^b\)        | G140L  |
| GJ 49        | M1         |               | 9.86       | 18.6\(^d\)               | 0.54                  | 0.53                  | 3713                   | field\(^b\)          | G140L  |
| GJ 410       | M0         |               | 11.94      | 14.0\(^d\)               | 0.56                  | 0.55                  | 3786                   | 300 Myr\(^b\)        | G140L  |
| CD −35 2722  | M1         |               | 22.4       | 1.7\(^b\)                | 0.57                  | 0.56                  | 3727                   | 150 Myr\(^f\)        | G140L  |
| HIP 23309    | M0         |               | 26.9       | 8.6\(^b\)                | 0.79                  | 0.93                  | 3886                   | 24 Myr\(^f\)         | G140L  |

\(^5\) https://stistools.readthedocs.io/en/latest/

\(^6\) https://github.com/allison/lyapy

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Notes. Distances (d) from Gaia Data Release 2 (Brown et al. 2018); spectral types, effective temperatures \(T_{\text{eff}}\), masses \(M\), and radii \(R\) from Pineda et al. (2021).

(a) Donati et al. (2008), (b) Hartman et al. (2011), (c) Messina et al. (2010), (d) Newton et al. (2016), (e) Gagné & Faherty (2018), (f) Bell et al. (2015), (g) Irwin et al. (2011), (h) Shkolnik & Barman (2014), (i) Miles & Shkolnik (2017).
by the parameter D/H, i.e., the deuterium to hydrogen ratio: \( N(D) = N(H) \times D/H \). The value of D/H is fixed to \( 1.5 \times 10^{-5} \) (Linsky et al. 2006), so \( \log_{10} N(H) \) is the reported parameter. The Doppler parameter \( b \) controls the width of the absorption line, and we link \( b_{1H} \) and \( b_{1J} \) so that \( b_{1J} = b_{1H}/\sqrt{2} \), \( b_{1H} \) is the reported parameter. In order to reduce the number of free parameters for the G140L reconstructions, \( b_{1H} \) was fixed at 11.5 km s\(^{-1}\), based on the standard T = 8000 K ISM (Redfield & Linsky 2004; Wood et al. 2004).

To model the observed (attenuated) profile, we multiply the emission and absorption models (Equations (1) and (2)) and convolve with the instrument line spread function (LSF) provided by STScI\(^7\) for the appropriate grating and slit combinations to recover the true physical parameters and account for the non-Gaussian wings of the G140L LSF:

\[
F^h = (\nu_{\text{emission}} \times \nu_{\text{absorption}}) \ast \text{LSF}.
\]

### 3.2. Fitting Procedure and Results

To reconstruct the \( \lambda_\alpha \) profiles, we used a likelihood-based Bayesian calculation and a Markov chain Monte Carlo (MCMC) method (emcee\(^8\); Foreman-Mackey et al. 2013) to simultaneously fit the model (Equation (3)) to the observed spectra. We assume uniform (flat) priors for all parameters except for a logarithmic prior for the Doppler b value (Youngblood et al. 2016), and a Gaussian likelihood

\[
\ln L = -\frac{1}{2} \sum_i \left( \frac{y_i - y_{\text{model},i}}{\sigma_{y_i}} \right)^2 + \ln(2\pi\sigma_{y_i}^2),
\]

where \( N \) is the total number of spectral data points \( y_i \) with associated uncertainties \( \sigma_{y_i} \), and \( y_{\text{model},i} \) corresponds to Equation (3). We maximize the addition of \( \ln L \) and the logarithm of our priors with emcee. We used 50 walkers, ran for 50 autocorrelation times (~\( 10^5 \)-\( 10^6 \) steps), and removed an appropriate burn-in period based on the behavior of the walkers.

Tables 2–6 show all of our model parameters with the assumed priors (uniform or logarithmic) within a bounded range, and the 2.5, 15.9, 50, 84.1, and 97.5 percentiles as determined from the marginalized posterior distributions. We present the median (50th percentile) as the best-fit parameter values. The best-fit (median) and 68% and 95% confidence intervals on the reconstructed \( \lambda_\alpha \) and Si III fluxes were determined from the entire ensemble (i.e., a histogram of all the \( \lambda_\alpha \) or Si III fluxes from the MCMC chain). Often, the median parameter values do not create a self-consistent solution, so we obtain the best-fit models and reconstructed profiles from the median flux in each wavelength bin from the ensemble of models and reconstructed profiles. Figure 1 shows the best-fit model and reconstructed profile for the HIP 23309 data, and Figure 2 shows the marginalized and joint probability distributions of the fitted parameters for HIP 23309. Similar figures for the other stars are available in the figure set in the online journal.

In the rest of this section, we make note of any irregularities or the source of any constraints imposed on the reconstructions

\(^7\) [https://www.stsci.edu/hst/instrumentation/stis/performance/spectral-resolution](https://www.stsci.edu/hst/instrumentation/stis/performance/spectral-resolution)

\(^8\) [https://emcee.readthedocs.io/en/latest/](https://emcee.readthedocs.io/en/latest/)

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**Figure 1.** HIP 23309 best-fit \( \lambda_\alpha \) reconstruction. In the upper two panels, the STIS data with 1σ error bars are shown in black, and the best model fit (intrinsic \( \lambda_\alpha \) profile folded through the ISM) is shown in pink with 1σ error bars shown in dark shaded gray and 2σ error bars in light shaded gray. Dashed blue line shows the best-fit intrinsic \( \lambda_\alpha \) profile with 1 and 2σ error bars (dark and light shaded blue, respectively). Dotted black line shows the Si III best-fit profile. Bottom panel shows the residuals ((data-model)/(data uncertainty)) for the best-fit model (pink in the upper panels) that best fits the data (black in the upper panels). Horizontal dashed line is centered at zero. Dotted lines are centered at ±1.

(on a star-by-star basis. Most of the FUMES \( \lambda_\alpha \) spectra were obtained with the low-resolution G140L STIS grating (\( \lambda/\Delta \lambda \sim 1000 \)), where the H I and D I ISM absorption lines are unresolved. Resolving the D I absorption is useful for constraining the ISM model parameters (column density, Doppler b value, and radial velocity), so we provide constraints on these parameter values with outside information when necessary to aid convergence to a best-fit solution. These constraints include stellar radial velocities from SIMBAD, predicted ISM radial velocities from the Local ISM Kinematic Calculator\(^9\) (Redfield & Linsky 2008), predicted H I column densities for the Local Interstellar Cloud (LIC)\(^10\) (Redfield & Linsky 2000), and measured H I column densities from nearby sightlines collated from Wood et al. (2005), and Youngblood et al. (2016, 2017).

**GJ 4334**—The fit had to be restricted to \( \log_{10} N(H) > 17.8 \), because the fit preferred a \( \log_{10} N(H) < 17.8 \) solution. The likelihood values are not higher at \( \log_{10} N(H) < 17.8 \), but the parameter space is much more well-behaved (i.e., smoothly varying), which is likely why the fit prefers this parameter regime. With \( \log_{10} N(H) \) restricted to lie between 17.8–19, the best-fit \( \log_{10} N(H) = 18.03 \) is in agreement with the LIC model \( \log_{10} N(H) = 18.04 \) prediction and measurements of nearby sightlines (\( \log_{10} N(H) = 17.9–18.5 \)).

**HIP 17695**—Despite the high spectral resolution obtained for this target, the fit is not consistent with probable \( \log_{10} N(H) \) values (>17.5). The MCMC prefers the \( \log_{10} N(H) \)

\(^9\) [http://isim.wesleyan.edu/LISMDynamics.html](http://isim.wesleyan.edu/LISMDynamics.html)

\(^10\) [http://isim.wesleyan.edu/ColoradoLIC.html](http://isim.wesleyan.edu/ColoradoLIC.html)
value to be low (<17.0), which may be unphysically low based on knowledge of the local ISM (Wood et al. 2005), although a value <18.0 is justified based on literature measurements of nearby sightlines. We constrain the column density to be between 17.8–18.0, in agreement with the LIC model’s predictions log_{10} N(H I) = 17.93, and allow the MCMC to pile up near the lower boundary. We note that O V (1218.3 Å) is clearly detected in the Lyα red wing.

**LP 247-13**—We constrain the log_{10} N(H I) parameter to be between 18.3–19.0 (the fit prefers <18.0) based on a previous measurement of log_{10} N(H I) = 18.31 for a foreground star (Dring et al. 1997).

**GJ 49**—The fit reveals four different local maxima with no clear global maximum. We discard the solutions with a low log_{10} N(H I) = 17.7 value and a high log_{10} N(H I) = 18.7 value, because nearby sightlines indicate log_{10} N(H I) = 18.0–18.3. We also rule out the solution with the >100 km s^{-1} difference between V_{HI} and V_{radial}. With these restrictions on N(H I) and V_{HI} in place (see priors in Table 2), we ran the MCMC for the presented solution.

**GJ 410**—The posterior distribution for this star’s fit is wide, as the 95% confidence interval spans a factor of 15 in Lyα flux. Nearby sightlines indicate log_{10} N(H I) lies in the range of 17.6–18.6, and the solution’s log_{10} N(H I) = 18.32 is in agreement with this range.

### 3.3. Analysis of the Reconstruction Quality

The quality of the E140M reconstructions is high, but for many of our G140L reconstructions, >32% of the residuals lie outside of the ±1σ range (see Figure 1 and the extended figure set in the online journal). This indicates either that the data uncertainties are underestimated or that the model is mis-specified. In general, the data appear to be fit well by the model, but a Durbin–Watson test (Durbin & Watson 1950) reveals some positive autocorrelation in the residuals. For half of our stars (HIP 23309, GJ 410, LP 247-13, HIP 112312), the Durbin–Watson statistic (dw) is between 1.5–1.8 (where 2 represents no autocorrelation and 0 represents perfect positive autocorrelation) and for the others (GJ 49, CD −35 2722, GJ 4334, HIP 17695) dw = 1.1–1.4. This autocorrelation of the residuals can be partially accounted for by a group of weak, unresolved emission lines present around 1190–1210 Å that are not included in our model. Based on detailed spectra of the Sun

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Figure 2. One- and two-dimensional projections of the sampled posterior probability distributions, referred to as marginalized and joint distributions, respectively, of the nine parameters for HIP 23309. Contours in the joint distributions are shown at 0.5, 1, 1.5, and 2σ, and the histograms’ dashed black vertical lines show the 16th, 50th, and 84th percentiles of the samples in each marginalized distribution. Text above each histogram shows the median ± the 68% confidence interval.

(Complete figure set (8 images) is available.)
Table 2
Prior Probabilities, Best Fits, and Confidence Intervals for G140L

| Parameter                  | GJ 4334 | GJ 49 |
|---------------------------|---------|-------|
| $V_{\text{radial}}$ (km s$^{-1}$) | U(−100; 300) | U(−150; 150) |
| log_{10} A (erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) | U(−18.5; 8) | U(−14; −10) |
| FWHM$_L$ (km s$^{-1}$) | U(1; 1000) | U(1; 1000) |
| log_{10} (UHI) (km s$^{-1}$) | [−12.99, −12.89, −12.72, −12.36, −10.95] | [−11.93, −11.07, −10.52, −10.32, −10.26] |
| log_{10} (UHII) (cm$^{-2}$) | U(17.8; 19) | U(17.7; 18.5) |
| $b_{HI}$ (km s$^{-1}$) | 11.5 | 11.5 |
| $V_{\text{Si} \linebreak[0.5em] m}$ (km s$^{-1}$) | 188.9, 214.7, 223.1, 227.8, 233.4 | 47.0, 72.4, 72.8, 73.1, 73.3 |
| $V_{\text{Si} \linebreak[0.5em] III}$ (km s$^{-1}$) | U(−60; 400) | U(−250; 250) |
| $A_{\text{Si} \linebreak[0.5em] m}$ (km s$^{-1}$) | [195.5, 221.6, 247.7, 270.6, 292.7] | [76.2, 90.0, 104.2, 118.7, 132.9] |
| FWHM$_{\text{Si} \linebreak[0.5em] III}$ (km s$^{-1}$) | U(1; 700) | U(1; 700) |
| $F$ (Ly$\alpha$) (erg cm$^{-2}$ s$^{-1}$) | 5.47, 5.87, 7.03, 10.96, 59.54 | 0.46, 1.56, 2.49, 3.07, 3.28 |
| $F$ (Si III) (erg cm$^{-2}$ s$^{-1}$) | [1.78, 1.93, 2.11, 2.28, 2.44] | [5.06, 5.27, 5.50, 5.71, 5.90] |

Note. U represents a uniform prior within the bounds. Other values are fixed. On the second line: [2.5%, 15.9%, 50%, 84.1%, 97.5%].

 precision increases the visibility of features not covered by our model. Other FUMES targets with wider intrinsic line widths (and lower S/N) may swamp the signals from unresolved emission lines and/or continuum. Despite large scatter in the residuals, GJ 49’s Ly$\alpha$ and Si III flux measurements appear to be consistent with other FUMES targets of similar rotation periods (Pineda et al. 2021).

Regarding our fitted radial velocity parameters, we note that the relative accuracy of the STIS MAMA’s wavelength solution is reported in the STIS Instrument Handbook as 0.25–0.5 pixels (37–74 km s$^{-1}$ for the G140L grating; 0.8–1.6 km s$^{-1}$ for the E140M grating), and the absolute wavelength accuracy is 0.5–1 pixel (74–148 km s$^{-1}$ for G140L; 1.6–3.3 km s$^{-1}$ for E140M). We find that the quoted relative wavelength accuracy can easily describe the offsets between our fitted H1 and Si III radial velocities (accounting for the 68% confidence interval on those values). The quoted absolute wavelength accuracy can account for almost all of the offsets between the literature stellar radial velocities and our fitted radial velocities. The exception is GJ 4334, which has some disagreement in the literature over its radial velocity: $−40 \pm 4$ km s$^{-1}$ from Newton et al. (2014), $−16.5 \pm 4.0$ km s$^{-1}$ from Terrien et al. (2015), and $−11.9$ km s$^{-1}$ from West et al. (2015). This discrepancy is not large enough to account for the $\sim 200–300$ km s$^{-1}$ offset between our fitted radial velocities and the literature values. However, GJ 4334’s velocity difference between the fitted radial velocity and the fitted ISM radial velocity is in agreement with the velocity difference between the Newton et al. (2014) radial velocity and the ISM velocity (6.0 ± 1.4 km s$^{-1}$) predicted by Redfield & Linsky (2008), lending confidence to our fit and supporting the possibility that the absolute wavelength accuracy for GJ 4334’s STIS observation is poorer than is typical.
To test the accuracy of the reconstructions based on the G140L spectra, we degraded the resolution of our E140M spectra (HIP 112312 and HIP 17695) to the resolution of the G140L spectra by convolving with the G140L LSF and rebinning to match the G140L dispersion. Tables 5 and 6 and show the results of the E140M (native resolution) and degraded

### Table 3
Prior Probabilities, Best Fits, and Confidence Intervals for G140L

| Parameter | GJ 410 | LP247-13 |
|-----------|--------|----------|
| $V_{\text{radial}}$ (km s$^{-1}$) | U(−250; 250) | U(−250; 250) |
| log$_{10}$ A | U(−18.5; −8) | U(100; 1000) |
| FWHM$_L$ (km s$^{-1}$) | [−11.6, −11.38, −11.04, −10.44, −9.3] | [−12.27, −12.19, −12.0, −11.58, −11.04] |
| log$_{10}$ N(H I) | U(17.5; 19) | U(18.3; 19) |
| b$_{\text{HI}}$ (cm$^{-2}$) | [18.05, 18.18, 18.32, 18.48, 18.68] | [18.3, 18.31, 18.35, 18.42, 18.50] |
| $V_{\text{HI}}$ (km s$^{-1}$) | U(−200; 200) | U(−250; 250) |
| $V_{\text{Si}$ m | U(−160; 350) | U(−16; −13) |
| log$_{10}$ A | U(−16; −13) | U(175; 19) |
| FWHM$_{\text{Si}$ m | U(175; 19) | U(170; 700) |
| $F(\text{Ly}_\alpha)$ (erg cm$^{-2}$ s$^{-1}$) | $\times 10^{-12}$ | $\times 10^{-12}$ |
| $F(\text{Si III})$ (erg cm$^{-2}$ s$^{-1}$) | $\times 10^{-15}$ | $\times 10^{-15}$ |

**Note.** U represents a uniform prior within the bounds. Other values are fixed. On the second line: [2.5%, 15.9%, 50%, 84.1%, 97.5%].

### Table 4
Prior Probabilities, Best Fits, and Confidence Intervals for G140L

| Parameter | CD 35-2722 | HIP 23309 |
|-----------|------------|-----------|
| $V_{\text{radial}}$ (km s$^{-1}$) | U(−250; 250) | U(−250; 250) |
| log$_{10}$ A | U(−18; −8) | U(100; 1000) |
| FWHM$_L$ (km s$^{-1}$) | [−12.79, −12.75, −12.70, −12.63, −12.51] | [−12.26, −12.23, −12.20, −12.17, −12.14] |
| log$_{10}$ N(H I) | U(17.5; 19) | U(175; 19) |
| $b_{\text{HI}}$ (cm$^{-2}$) | [17.52, 17.60, 17.78, 17.98, 18.21] | [17.61, 17.71, 17.80, 17.88, 17.96] |
| $V_{\text{HI}}$ (km s$^{-1}$) | U(−250; 250) | U(−250; 250) |
| $V_{\text{Si}$ m | U(−66.2; 58.3, 38.2, 59.0, 67.9) | [47.5, 72.0, 74.7, 76.7, 78.8] |
| log$_{10}$ A | U(100; 250) | U(100; 250) |
| FWHM$_{\text{Si}$ m | [−7.5, 8.7, 25.1, 42.1, 67.9] | [96.3, 107.5, 118.1, 128.5, 138.6] |
| $F(\text{Ly}_\alpha)$ (erg cm$^{-2}$ s$^{-1}$) | $\times 10^{-13}$ | $\times 10^{-13}$ |
| $F(\text{Si III})$ (erg cm$^{-2}$ s$^{-1}$) | $\times 10^{-14}$ | $\times 10^{-14}$ |

**Note.** U represents a uniform prior within the bounds. Other values are fixed. On the second line: [2.5%, 15.9%, 50%, 84.1%, 97.5%].
resolution reconstructions for these two stars. There is substantial overlap between the native and degraded reconstructed Lyα fluxes at the 68% (for HIP 17695) and the 95% confidence interval (for both). The uncertainties with the G140L-quality reconstruction are much larger than for the E140M reconstructions, as expected. When comparing the individual fitted parameter values, we find that the G140L-quality reconstructions do not always agree with their higher-resolution counterparts. For HIP 17695, agreement between the individual fitted parameters is generally good, but this is not the case for HIP 112312. We provide confidence intervals for all of our G140L reconstruction parameters (Tables 2–4), but note that they should be interpreted with caution and may not reflect the true parameters that could be revealed with higher-resolution spectra. This may be because the G140L posterior distributions are generally very wide, and we report the median parameter values as the best-fit values, even though combining the median parameter values does not always yield a self-consistent best-fit to the data. However, this exercise in comparing E140M reconstructions with degraded resolution reconstructions shows that the reconstructed Lyα fluxes overlap within at least the 95% level.

4. Discussion

4.1. The Wilson–Bappu Effect and Lyα Line Widths

Our STIS G140L reconstructed spectra of M dwarfs show their broad, ~500–1000 km s⁻¹ Lyα wings in detail (Figure 3). As demonstrated in Ayres (1979), the widths of chromospheric emission lines like Ca II H&K, Mg II h&k, and Lyα are predominantly controlled by the stellar temperature distribution rather than chromosphere dynamics or magnetic heating. This explains the remarkable Wilson–Bappu correlation between absolute stellar magnitude and FWHM for the Ca II H&K emission cores (Wilson & Bappu 1957) and other chromospheric emission lines (McClintock et al. 1975; Cassatella et al. 2001) across many orders of magnitude of stellar bolometric luminosity. In Figure 4, we show that our data support a similar
correlation ($\rho = 0.72$; $p = 0.0015$) between bolometric luminosity and Ly$\alpha$ FWHM, albeit over a much smaller parameter space than that explored by Wilson & Bappu (1957).

Ayres (1979) notes that stellar magnetic activity (e.g., due to nonradiative heating) does play a role in the widths of chromospheric emission lines, with greater activity corresponding to wider lines, in addition to the stronger influences of stellar effective temperature, surface gravity, and elemental abundance compared to hydrogen. Ayres (1979) and Linsky (1980) present a linear model of chromospheric emission line width as a function of chromospheric heating (i.e., activity as measured by the flux of a chromospheric emission line), effective temperature, surface gravity, and elemental abundance. To determine which stellar properties are most responsible for our observed Ly$\alpha$ widths, we construct a linear model based on our observations. We select surface gravity, Si III luminosity as a fraction of bolometric luminosity (a general “activity” proxy), and effective temperature as predictor variables. Because we are examining a hydrogen line, we do not include a metallicity term. We scale each variable (by subtracting the mean and dividing by the standard deviation), construct a correlation matrix, and calculate the eigenvalues and eigenvectors via principal component analysis (PCA) (Table 7). Only the first two principal components (PCs) or eigenvectors have eigenvalues $>1$ or are correlated significantly ($|\rho| > 0.5$; $p < 0.05$) with any of the predictor variables; therefore, we only include PC1 and PC2 in the linear model of Ly$\alpha$ width.

We perform a multiple linear regression to relate our previously determined PCs to a response variable, the Ly$\alpha$ full width at 20% maximum flux (FW$\alpha_{20%}$), a term that is analogous to $W(K_1)$ from Ayres (1979). Regression coefficients are reported in Table 7. Simplifying the linear model expressions into the original unscaled predictor variables rather than PCs, we find that, for the Ly$\alpha$ emission line:

$$\log_{10}(FW_{20%}) = -0.29 \log_{10} g + 0.09 \log_{10} \frac{L(Si \text{ III})}{L(\text{bol})} + 2.13 \log_{10} T_{\text{eff}} - 5.54, \quad (5)$$

where FW$\alpha_{20%}$ is in Å, $g$ is in cm s$^{-2}$, $L(Si \text{ III})/Lbol$ is unitless, and $T_{\text{eff}}$ is in K. There are some similarities in the coefficients between this paper’s Equation (5) and Equation (8) from Linsky (1980) ($log(W(k_1)) = -0.25 \log g + 0.25 \log F + 1.75 \log T_{\text{eff}} + 0.25 \log A_{\text{met}}$, where $F$ is the scaled nonradiative heating rate and $A_{\text{met}}$ is the metal abundance), such as the sign and magnitude of each coefficient being roughly the same. Dissimilarities are likely due to the differences in terms ($F$ and $A_{\text{met}}$) and parameter ranges in the sample stars. In this analysis, the stars used have $log_{10} g$ between 3.9–5.2, $log_{10} L(Si \text{ III})/Lbol$ between −7.5 and −5.0, and $T_{\text{eff}}$ between 3000–3900 K. The observed range of FW$\alpha_{20%}$ values is 0.6–3.8 Å.

As is the case for Ca II, stellar activity appears to be a minor factor in the width of Ly$\alpha$, as also indicated by the lack of correlation between FW$\alpha_{20%}$ and L$\alpha(Ly\alpha)/L_{bol}$ ($\rho = 0.06$, $p = 0.82$) or $L(Si \text{ III})/L_{bol}$ ($\rho = 0.29$, $p = 0.27$). The more dominant factors are surface gravity and effective temperature, as indicated by the correlation coefficients between FW$\alpha_{20%}$ and $T_{\text{eff}}$ ($\rho = 0.50$; $p = 0.05$) or $g$ ($\rho = -0.51$; $p = 0.04$). From Figure 3, we find that, in general, the M dwarfs with larger Ly$\alpha$ wing flux values tend to be more active. The “inactive” MUSCLES M dwarfs (as determined by optical activity indicators such as Ca II; see France et al. (2016)) have the
narrowest profiles, and Proxima Centauri has a surprisingly narrow profile given its known levels of moderate activity (Robertson et al. 2013, 2016; Davenport et al. 2016; Howard et al. 2018). For example, compare Proxima Centauri’s log₁₀

\[ L(\text{Si} 
\n\text{III})/L_{\text{bol}} = -6.2 \]

to the −7.2 to −7.5 values for the inactive MUSCLES M dwarfs GJ 832, GJ 581, and GJ 436. However, as discussed, these line widths are dominated by stellar structure, and in general, M dwarfs with lower surface gravity (i.e., younger ones) tend to be more active.

4.2. Chromospheric Electron Density Estimates from Lyα Observations

The electron density in the line forming region (the chromosphere for the Lyα broad wings) is a main factor in controlling the width of the Lyα line (Gayley 1994). We estimate chromospheric electron density values, which are a valuable constraint for stellar models, using the formalism from Gayley (1994) that explicitly relates the surface flux density of the Lyα broad wings to chromospheric electron density and other stellar properties:

\[ F_{\text{wing}}(\Delta \lambda) \approx \frac{F_{\text{peak, }\odot}}{\Delta \lambda} \left( \frac{n_e}{n_e,\odot} \right)^2 \frac{g}{g_\odot} \frac{T_{\text{chromo}}}{7500 \text{ K}} \frac{J_{2c,\odot}}{J_{2c}}, \]

where \( F_{\text{wing}}(\Delta \lambda) \) is the Lyα surface flux density at \( \Delta \lambda \) Å from line center, \( F_{\text{peak, }\odot} \) is the peak solar Lyα flux (\( \sim 3 \times 10^5 \text{ erg cm}^{-2} \text{ s}^{-1} \)), \( n_e \) is the chromospheric electron density, \( g \) is the surface gravity, \( T_{\text{chromo}} \) is the chromospheric temperature, and \( J_{2c} \) is the Balmer continuum flux. Each parameter is normalized to the solar (\( \odot \)) value. Stars with larger electron densities and hotter chromospheres will have broader wings, but the wing intensity is diminished for stars with greater surface gravity and greater Balmer continuum flux.

Figure 5 shows the Lyα surface flux densities of the FUMES targets, the MUSCLES M dwarfs (France et al. 2016), Proxima Centauri and AU Mic (Youngblood et al. 2017), and the Sun (SORCE/SOLSTICE; McClintock et al. 2005), plotted against surface gravity. Lines of constant electron density are drawn on the plot using Equation (6). We assume \( T_{\text{chromo}} \) and \( J_{2c} \) are both equivalent to solar values (\( T_{\text{chromo}} = 7500 \text{ K}; J_{2c} = 1.7 \times 10^2 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \text{ sr}^{-1} \)). For stars with known chromospheric electron densities, the Gayley (1994) approximation works well. The Sun’s electron density \( n_e = 11 \text{ cm}^{-3} \) (Song 2017), and GJ 832’s \( n_e = 10 \text{ cm}^{-3} \) (Fontenla et al. 2016), are both in agreement with the gray curves in Figure 5.

We find that LP 247-13, a 625 Myr M2.7V star, has a chromospheric electron density similar to that of the Sun. All of the FUMES targets (“active” stars) have electron densities larger than those of the “inactive” M dwarfs from the MUSCLES survey, except for GJ 176. We note that GJ 176 is the least “inactive” of the MUSCLES stars, as it is the most rapidly rotating (\( P_{\text{rot}} = 39.5 \text{ day}, \text{per Robertson et al. (2015)} \)) and is possibly younger than 1 Gyr based on its large X-ray luminosity (Guinan et al. 2016; Loyd et al. 2018).

4.3. STIS G140L and Future Lyα Observations

The presented Lyα reconstructions are the first based on \( \lambda/\Delta \lambda \sim 1000 \) spectra with the ISM H1 absorption completely unresolved. Using the STIS G140L mode provides some observational advantages, including avoiding prohibitively long exposure times of higher-resolution STIS modes for M-dwarf targets deemed too hazardous for the COS instrument (Bright Object Protections 12). Based on the six M dwarfs presented here, we find that the precision of Lyα reconstructions performed on STIS G140L spectra can range from 5% to 100% at the 68% confidence level (Figure 6). At the 95% confidence level, the precisions range from \( \sim 10\% \) to a factor of nine. There appears to be no dependence of these precisions on the S/N of the observed spectrum; we note that all G140L Lyα emission lines were detected at high S/N (90–250 integrated over the line). Rather, our three G140L targets with the largest reconstructed flux uncertainties (GJ 4334, GJ 49, and GJ 410) are also the G140L targets with the lowest surface flux in the Lyα wings, or
in other words, the narrowest profiles. We hypothesize that, for narrow profiles (Ly$\alpha$ surface flux at $\pm 2$ Å $\lesssim 10^7$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ or FW$_{20\%} < 2.5$–3.0 Å), the spectrum does not provide enough spectrally resolved information for the fit to distinguish between solutions with large flux and large ISM columns versus those with small flux and small ISM column solutions. The higher-resolution E140M grating results in reconstructed flux precisions of approximately 2%–4% at the 68% confidence level for high S/Ns (we note that the two stars with E140M observations, HIP 112312 and HIP 17695, have a line-integrated S/N = 70–90). However, for lower S/N spectra, Youngblood et al. (2016) found uncertainties up to 150% in E140M reconstructions of K dwarfs (HD 97658, HD 40307, HD 85512) with S/N = 20–30 integrated over the line. The precision found by Youngblood et al. (2016) with the STIS G140M grating ($\lambda/\Delta \lambda \sim 10,000$) is 5%–30% for medium to high S/Ns, and can be a factor of ~2 for low S/Ns (e.g., GJ 1214, S/N = 4 integrated over the line). Thus, STIS G140L spectra can produce reconstructed Ly$\alpha$ fluxes for young, active M dwarfs with precisions comparable to G140M spectra, but the precision is much lower than what is obtainable with high S/N G140M or E140M spectra.

Adopting FW$_{20\%} > 2.5$ Å as the threshold between precise and imprecise Ly$\alpha$ reconstructions with G140L, Equation (5) may be useful for guiding future observers toward whether or not G140L is suitable for a Ly$\alpha$ reconstruction for a particular M dwarf. Surface gravity and effective temperature, two of the three stellar parameters in Equation (5), are readily available in
the literature for many M dwarfs. The third parameter, $L(\text{Si III})/L(\text{bol})$, is not available for most M dwarfs, but can be estimated from the stellar rotation period (Pineda et al. 2021) or common activity indicators like $R_{HK}$ or $L(\text{H}\alpha)/L(\text{bol})$ (Melbourne et al. 2020).

Figure 6 shows how the observed Ly$\alpha$ fluxes compare to the reconstructed (intrinsic) fluxes. The observed fluxes were obtained simply by integrating over the observed, ISM-attenuated Ly$\alpha$ profiles. In some cases, the observed Ly$\alpha$ fluxes are only 10%–50% less than the reconstructed fluxes, while in others they are a factor of a few to an order of magnitude less. The dominant factor in the flux differences is the column density of the ISM absorbers and the radial velocity of the ISM absorbers relative to the stellar radial velocity. A small radial velocity offset between the star and ISM, along with larger column densities, will result in larger flux differences between observed and reconstructed fluxes. Figure 6 may give readers a sense of whether or not performing a reconstruction on G140L Ly$\alpha$ spectra is worthwhile for their science goals.

5. Summary

As part of the Far Ultraviolet M-dwarf Evolution Survey (FUMES), we have reconstructed the intrinsic Ly$\alpha$ profiles of eight early-to-mid M dwarfs spanning a range of young to field star ages from low- and moderate-resolution spectra taken with HST’s STIS spectograph. The Ly$\alpha$ and Si III fluxes derived in this paper are incorporated into Paper I of the FUMES survey (Pineda et al. 2021), which describes the flux evolution of FUV spectral lines with stellar age and rotation period for early- to mid-M dwarfs. We summarize our findings here:

1. We present the first demonstration of Ly$\alpha$ reconstruction on low, $\lambda/\Delta\lambda \sim 1000$ resolution spectra, where the H I absorption trough from the ISM is completely unresolved. We find that the 1$\sigma$ precision in the reconstructed Ly$\alpha$ flux can be 5%–10% in the best case (young M dwarfs) and a factor of two in the worst case (field age M dwarfs). The precision is not correlated with the S/N of the observation—rather, it depends on the intrinsic broadness of the stellar Ly$\alpha$ line. Young, low-gravity stars have the broadest lines and therefore provide more information at low spectral resolution to the fit, to break degeneracies among model parameters.

2. Our high S/N, low-resolution Ly$\alpha$ spectra detect the extremely broad wings ($\sim$500–1000 km s$^{-1}$) at S/N = 7–14 per resolution element, and we see large differences in the width of Ly$\alpha$ from star to star. We confirm past findings that the line width is predominantly correlated with the fundamental stellar parameters of surface gravity and effective temperature, rather than magnetic activity.

3. Ly$\alpha$ surface flux density $\sim$2 A from line center may predict electron density values in the chromosphere, as shown by Gayley (1994). We confirm the validity of the Ly$\alpha$ surface flux density approximation from that work using GJ 832’s spectrum from Youngblood et al. (2016) and Loyd et al. (2016), in addition to the modeled electron density from Fontenla et al. (2016).

The data presented here were obtained as part of the HST Guest Observing program #14640. A.Y. acknowledges support by an appointment to the NASA Postdoctoral Program at Goddard Space Flight Center, administered by USRA through a contract with NASA. We thank J. Linsky, T. Barclay, and A. Wolfgang for helpful discussions, and E. R. Newton and W. C. Waalkes for their contributions to lyapy. Finally, we thank the anonymous referee for suggestions that greatly improved the paper.

Facility: HST.

Software: Astropy (Robitaille et al. 2013), IPython (Perez & Granger 2007), Matplotlib (Hunter 2007), NumPy and SciPy (van der Walt et al. 2011), lyapy (Youngblood et al. 2016), emcee (Foreman-Mackey et al. 2013), triangle (Foreman-Mackey et al. 2014), statsmodels (Pertkold & Seabold 2010).

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