The Far Ultraviolet M-dwarf Evolution Survey. I. The Rotational Evolution of High-energy Emissions*

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Abstract

M-dwarf stars are prime targets for exoplanet searches because of their close proximity and favorable properties for both planet detection and characterization. However, the potential habitability and atmospheric characterization of these exoplanetary systems depends critically on the history of high-energy stellar radiation from X-rays to NUV, which drive atmospheric mass loss and photochemistry in the planetary atmospheres. With the Far Ultraviolet M-dwarf Evolution Survey, we have assessed the evolution of the FUV radiation from known rotation periods to within ~0.3 dex, across eight distinct UV emission lines, with possible trends in the fit parameters as a function of source layer in the stellar atmosphere. Our detailed analysis of the UV luminosity evolution with age further shows that habitable-zone planets orbiting lower-mass stars experience much greater high-energy radiative exposure relative the same planets orbiting more massive hosts. Around early- to mid-M dwarfs, these exoplanets, at field ages, accumulate up to 10–20× more EUV energy, relative to modern Earth. Moreover, the bulk of this UV exposure likely takes place within the first Gyr of the stellar lifetime.

Unified Astronomy Thesaurus concepts: M dwarf stars (982); Stellar activity (1580); Ultraviolet astronomy (1736)

1. Introduction

The presence of self-sustained magnetic fields in low-mass stars has important consequences for their upper atmospheric structure and their high-energy radiative environments. Due to nonthermal magnetic heating processes (see Linsky 1980; Hall 2008), thought to be either wave dissipation (e.g., Narain & Ulmschneider 1996) or Joule heating from magnetic reconnection (e.g., Klimchuk 2006), these low-mass stars exhibit significant temperature inversions in their outer atmospheres. These portions of the stellar atmosphere—the chromosphere, transition region, and corona—are largely responsible for the entire high-energy spectrum, from the near-ultraviolet (NUV) to the X-rays in low-mass stars; for a recent review, see Linsky (2017). While much effort has been devoted to studying stellar chromospheres/corona, the nature of these structures, the underlying processes that generate them, and their evolution remain poorly understood, especially for M-dwarf stars.

Addressing these questions has attained renewed urgency given the prevalence of terrestrial exoplanets orbiting M dwarfs, with at least ~20% of these stars hosting an Earth-sized planet within their habitable zones (HZ; e.g., Dressing & Charbonneau 2015; Vanderburg et al. 2020). Moreover, the best systems for detailed atmospheric characterization with the James Webb Space Telescope will be around nearby low-mass M dwarfs (e.g., Morley et al. 2017). Understanding the high-energy emissions of these systems is crucial because of the role they play in planetary atmospheric mass loss and photochemistry (e.g., Scalo et al. 2007; Owen & Jackson 2012; Luger & Barnes 2015; Tian & Ida 2015). For example, for a Neptune/Earth-sized planet in the HZ of an M dwarf, strong radiation shortward of ≲911 Å (X-rays + extreme ultraviolet, XUV) can dictate the ultimate water content of the planet through atmospheric evaporation (Owen & Jackson 2012). Furthermore, the balance of NUV (1700–3200 Å) to FUV (912–1700 Å) emissions can determine equilibrium levels of abiotically produced O2, complicating the search for biosignatures (see Meadows et al. 2018).

The completion of the MUSCLES Treasury Survey provided the first comprehensive constraints of M-dwarf X-ray and UV luminosities from panchromatic observations of exoplanet-hosting M dwarfs (France et al. 2016; Loyd et al. 2016; Youngblood et al. 2016, 2017). Their work further showed that the entire XUV and FUV broadband fluxes could be estimated based on a couple of FUV or NUV spectroscopic features (France et al. 2016; Youngblood et al. 2017). These measurements have since become important inputs for models of planetary atmospheres (e.g., Gao et al. 2015; Ranjan et al. 2017). However, interpreting future atmospheric observations, potential biosignature detections, and the ability of such atmospheres to develop life also depends on the evolution of the planetary atmosphere—and hence the evolution of the incident radiation field. The MUSCLES survey focused on...
older field objects with confirmed planet detections. However, at early ages, these M-dwarf hosts likely exhibited much stronger high-energy emissions (e.g., Shkolnik & Barman 2014), capable of desiccating terrestrial worlds early in their lifetimes (Tian & Ida 2015).

Understanding this evolution has been challenging because of the difficulty in determining stellar ages in the M-dwarf regime (Guinan et al. 2016). Although the ages of some objects can be determined through membership in clusters or young moving groups (see Zuckerman & Song 2004), the vast majority of M dwarfs lack precise age determinations. Instead, rotation can be used as a proxy for stellar age, as in gyrochronology (e.g., Skumanich 1972; Barnes 2003; Meibom et al. 2015; van Saders et al. 2016), although understanding the angular momentum evolution of M dwarfs remains a topic of continued work (Barnes 2010; Reiners & Mohanty 2012; Garraffo et al. 2015, 2018; Guinan et al. 2016). Nevertheless, there is a fundamental physical interplay between stellar age, rotation, and magnetic activity in low-mass stars (e.g., Skumanich 1972; Noyes et al. 1984; Vidotto et al. 2014), a consequence of the feedback between magnetic field generation in the internal dynamo and angular-momentum loss over time through coronally driven stellar winds.

Indeed, rotation–activity correlations have been used extensively as probes of these magnetic processes and their evolution in M dwarfs, confirming the strong rotational dependence of the magnetic emissions, even across the fully convective boundary toward late-M dwarfs, as well as a saturation of the activity at fast rotation rates and young ages (e.g., Pizzolato et al. 2003; Stelzer et al. 2013; Wright & Drake 2016; Astudillo-Defru et al. 2017; Houdéeline et al. 2017; Newton et al. 2017; Shulyak et al. 2017; Wright et al. 2018). These studies have focused predominantly on X-rays or optical emission lines like Hα to trace the magnetic activity. The quiescent UV spectra of active M dwarfs had been largely unexplored except for a few well-known flare stars (Rutten et al. 1989; Hawley & Pettersen 1991; Ayres et al. 2003; Hawley et al. 2003, 2007), limiting our ability to probe the rotational evolution of these features. Understanding these UV emissions is important, not only with regard to the incident radiation field impacting planetary atmospheres, but also because the various emission lines spanning a range of formation temperatures in the FUV spectra serve as unique probes throughout the different layers of the transition region (\( T_\text{f} \sim 10^{4.0-5.5} \)), where the temperature in the outer atmosphere is rising rapidly from the chromosphere to the corona (see Linsky 2017).

These developments motivate the Far Ultraviolet M-dwarf Evolution Survey (FUMES) with the Hubble Space Telescope (HST) to examine the rotational evolution of the FUV spectral features in early- to mid-M dwarfs, provide important benchmarks for their high-energy emission over time, and provide constraints on the chromospheric/coronal structure of active low-mass stars. In this paper, the first of several, we focus on the quiescent emissions of our FUMES sample as a function of rotation/age. In Section 2, we introduce the FUMES sample and assess their stellar properties. In Section 3, we discuss our HST observations and spectral measurements. In Section 4, we examine the rotation–activity correlations of UV emission in low-mass stars, incorporating data from the literature. In Section 5, we discuss the implications of our measurements for the temporal evolution of high-energy emissions around low-mass stars. In Section 6, we provide our conclusions, and finally we summarize our findings in Section 7.

2. Sample and Stellar Properties

In contrast to previous samples of M-dwarf stars selected for UV observations, either exoplanet hosts (e.g., MUSCLES; France et al. 2013) or known flare stars (e.g., Hawley et al. 2003, 2007), the FUMES target list of 10 objects was chosen to span a range of rotation periods from \(~1\) to 55 days, in order to trace the rotational evolution of low-mass stars and fill the gap in rotation parameter space between the active flare stars and the slowly rotating exoplanet hosts. The rotation period measurements were typically determined from photometric monitoring (e.g., Messina et al. 2010; Newton et al. 2016) or long-term variability of optical emission lines (e.g., Suárez Mascareño et al. 2015). We also included many objects with known ages from likely membership in a young moving group, to facilitate age comparisons and provide multiple benchmarks for high-energy emissions at early ages. We further focused on early- to mid-M-dwarf systems because, thanks to the success of previous studies like MUSCLES (France et al. 2016), there already exist multiple benchmarks in UV emission for slowly rotating (\((>70 \text{ days})\)) objects in this spectral type range, allowing us to focus on providing a comparison with more active targets.

Before delving into our analysis of the UV emissions (Section 3), it is important to estimate the physical properties of our targets. To this end, we obtained infrared spectra of all 10 stars, which enabled us to consistently determine spectral types, measure metallicity indicators, and compare estimates for effective temperature and bolometric luminosity (e.g., Newton et al. 2015; Terrien et al. 2015). These data are discussed in Section 2.1. The IR data were most valuable for estimating spectral types and ruling out the possible influence of cool unknown companions in the photometry. Ultimately, we rely on the results of J.S. Pineda et al. (2021, in preparation) for the physical properties of the stars used in this work. Those methods are summarized in Section 2.3.

2.1. IR Data

To measure the NIR spectra of our sample targets, we used the TripleSpec (TSPEC) instrument (Wilson et al. 2004) on the ARC 3.5 m telescope at the Apache Point Observatory, as well as the similarly designed ARCoRIS instrument\(^4\) on the Blanco 4 m telescope at NOAO’s Cerro Tololo Inter-American Observatory. A summary of these observations can be found in Table 1. Both instruments, which each have a 1’’1 slit, provide \( R \sim 3500 \) spectra continuously across NIR wavelengths in 5–6 echelle orders, with TSPEC spanning 0.95–2.46 \( \mu m \) and the updated ARCoRIS design covering 0.80–2.47 \( \mu m \).

For all of our data, we took the same observing approach, using an ABBA slit nod sequence with short exposures (<30 s), mitigating sky emission-line variability, to provide clean sky subtraction from subsequent frames, and remaining on target over several tens of minutes in order to obtain a high signal-to-noise ratio (S/N) observation for each target (see Table 1). We also observed a nearby A0 star close in time and

\(^4\) Instrument info can be found here: ARCoRIS (http://www.ctio.noao.edu/noao/content/Arcoiris).
We reduced the data using modified versions of SpeXtool (Cushing et al. 2004), one for TSPEC and a separate one for ARCoIRIS.\(^5\) We summarize the data reduction procedure as follows. We first created the master flatfield for each observing night by median combining several dome lamp exposures and subtracting off the median thermal contribution from dome exposures taken with the lamps off. The thermal contribution is most significant in the \(K\) band. The wavelength calibration for each target was then determined from the median sky spectrum, created from each target’s science observations.\(^6\) Initial sky subtraction was performed by differencing AB nod pairs, from which we determined the object trace in each order. We extracted the spectrum in windows centered along the trace, applying the normalized flatfield and wavelength calibration. When variable cloud cover was evident, we also applied additional sky subtraction, removing a linear fit to the residual background. The spectra from individual frames were averaged together in order to increase the S/N, and then we used the similarly extracted A0 calibrator spectra to correct for telluric absorption and provide a flux calibration using xtellcorr (Vacca et al. 2003). We then merged the different echelle orders, averaging the spectra in overlapping wavelength regions to create the final spectrum of each target. The IR spectra of the FUMES sample are shown in Figure 1.

2.2. Spectral Types

We determine the NIR spectral type classifications for the FUMES sample using the composite spectral standards compiled from multiple stars by Newton et al. (2014).\(^7\) These NIR spectra, taken with the NASA Infrared Telescope Facility (IRTF)/SpeX, are classified on the KHM system originally defined by Kirkpatrick et al. (1991, 1995, 1999) at red optical wavelengths. We first computed the \(H_2O–K2\) index defined by Rojas-Ayala et al. (2012) as a \(K\)-band feature sensitive to spectral type, and used the calibration from Newton et al. (2014) (their Equation (2)) to convert this measurement to an initial type estimate.\(^8\) We then used this classification to select a range of nearby spectral standards, spanning one type earlier and later, to compare against our observations in order to classify the spectra by eye using features across the entire infrared spectrum. This holistic approach helped mitigate potential feature mismatches introduced by metallicity differences between the targets and the standards by not relying on any single features in the spectra. We determined a single best type for each of the \(YJHK\) bands and took the median as our best classification.

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\(^{a}\) This column reflects the typical signal-to-noise ratio in the \(H\) band of each spectrum.

\(^{b}\) Given an AB nod pair, the sky contribution can be estimated as \(S = 0.5 \lfloor (A + B) – (|A – B|) \rfloor\). For short exposures, one needs to accumulate several frames to produce sufficient signal in sky emission.

\(^{c}\) For TSPEC, see TriplespecTool (https://www.astronomy.uiuc.edu/arc35m/instruments/TRIPLESPEC/TspecTool/index.html), and for the ARCoIRIS version, developed by Dr. Allers, see TS4 Reduction (http://www.ctio.noao.edu/noao/content/TS4-Data-Reduction).

\(^{d}\) We prefer the conversion from \(H_2O–K2\) index to NIR spectral type from Newton et al. (2014) rather than that from Rojas-Ayala et al. (2012), because the former is based on classifications using the entire NIR spectra.
Our NIR classifications for the FUMES sample are shown in Table 2, and we estimate spectral type uncertainties of half a subtype. We also include the literature optical spectral types for comparison, typically from the Palomar/Michigan State University (PMSU) survey (Reid et al. 1995; Hawley et al. 1996) for the field objects, but from additional sources for the younger stars. As discussed in Rojas-Ayala et al. (2012) and Newton et al. (2014), the literature optical spectral types are often dependent on metallicity across the M1–M4 range, and we consider the NIR classifications to be the more consistent metrics. We similarly report the NIR/optical spectral types for the literature sample in Table 2. These classifications will be important in Section 5.

A couple of objects deserve further attention. Since the Newton et al. (2014) standards do not include spectra for types earlier than M1, we also used the M0 and K7 standards within their Equation (3) from Newton et al. (2014) with the metallicity determined from their calibration of the equivalent widths of the Na doublet at 2.2 μm (their Equation (10)).
distort the observed spectra. However, there was evidence for a slightly deeper 0.99 μm FeH feature than would be expected for an M1 dwarf, perhaps due to the strength of this feature in L-dwarf spectra (e.g., Kirkpatrick 2005). The young star HIP 112312 has an optical classification as a subgiant from Torres et al. (2006). Without subgiant standards with which to compare in the NIR, we cannot confirm this classification with our observations. For this star, we also compared the M-giant IRTF NIR standards (Rayner et al. 2009), finding that the HIP 112312 NIR spectrum largely agrees with the dwarf sequence except for deeper CO lines in the K band, which are very prominent in the M-giant spectra, reflecting the relatively low gravity of this young object. The other young FUMES stars (see Table 2) showed spectra consistent with the dwarf standards.

2.3. Stellar Properties

Our aim in this paper is to analyze the relation between FUV emissions and the physical properties of low-mass stars. To these ends, we desired self-consistent properties, mass, radius, bolometric luminosity, and effective temperature for each FUMES target, as well as any suitable additional targets found in the literature. Consistently determined properties are crucial to mitigate potential systematic effects introduced by relying on an assortment of eclectic literature determinations for these stellar properties. Although our IR spectra allowed us to utilize spectroscopic property calibrations (e.g., Mann et al. 2015; Newton et al. 2015; Terrien et al. 2015), such data were not uniformly available for both the FUMES and literature targets, and thus we rely instead on the largely photometric results from our companion paper summarized below (J.S. Pineda et al. 2021, in preparation). The corresponding stellar properties are shown in Table 2.

2.3.1. Field Stars

To determine the properties of low-mass field stars, J.S. Pineda et al. (2021, in preparation) use a Bayesian framework to combine multiple empirical calibrations, largely photometry-based, to jointly constrain mass, radius, and bolometric luminosity, and derive the stellar effective temperature. Their methods fully incorporate measurement uncertainties and intrinsic scatter within the utilized calibrations, and produce well-defined joint posterior distributions for the full set of physical properties. J.S. Pineda et al. (2021, in preparation) jointly use the mass–luminosity relation of Mann et al. (2019), the bolometric correction calibration of Mann et al. (2015), and a new mass–radius relation valid across 0.09–0.7 M⊙ with 3.1% uncertainties at fixed mass, specifically developed in that work.

The Bayesian framework further allowed them to freely incorporate additional measurements—such as bolometric fluxes, or angular diameters from interferometry—whenever available. Many of the individual objects in the sample (see Table 2) had these additional measurements, which greatly improved the precision of the physical properties of a given sample object. Full details of these methods are available in J.S. Pineda et al. (2021, in preparation).

As compared to literature estimates of the M-dwarf ensemble analyzed in J.S. Pineda et al. (2021, in preparation), their methods yielded a stellar sequence with less scatter, consistent property estimates for objects with interferometric angular diameter measurements, and stellar densities consistent with independent data inferred from exoplanetary transits of low-eccentricity planets.

2.3.2. Young Stars

Of the objects shown in Table 2, five are high-probability members of known young moving groups: HIP 112312, HIP 17695, CD-35 2722, HIP 23309, and AU Mic (J.S. Pineda et al. 2021, in preparation). Because the available empirical calibrations are only applicable to field-age stars, these five young objects required a different approach for estimating their stellar properties. For these stars, Table 2 also quotes the stellar-model-based results from J.S. Pineda et al. (2021, in preparation). We summarize their methods as follows.

Within a Bayesian framework, J.S. Pineda et al. (2021, in preparation) couple stellar evolutionary models with spectral energy distribution fitting of model spectra using blue optical to far-infrared photometry. Using Monte Carlo sampling, a given mass and age within the evolutionary model defines the corresponding bolometric luminosity and radius, and thus the effective temperature and gravity of a sample point. These properties are then used for interpolation of a model atmosphere grid and generation of synthetic photometry for comparison with the observed data points. The best-fit stellar properties are those that best reproduce the photometry consistently within the evolutionary models. This approach self-consistently produces parameter estimates for all of the properties, with well-defined posterior distributions for each. For the five young objects, Table 2 reproduces the parameter results using magnetic stellar evolutionary models (Feiden & Chaboyer 2013, 2014; Feiden 2016). Full details of these methods and analysis of likely systematic effects in the model choices are explained in J.S. Pineda et al. (2021, in preparation).

Those properties most directly constrained by the SED fitting, namely Lbol, Teff, and R, are consistent (within errors) with the literature values (J.S. Pineda et al. 2021, in preparation). The young stars used in this work are all active M dwarfs, and we further discuss how our modeling choices—and thus the inferred masses—impact our rotation activity analysis in Section 4.1.

3. Far-ultraviolet Emissions

3.1. HST Data

We used the Space Telescope Imaging Spectrograph (STIS) on HST to measure the FUV spectra of our FUMES sample through program HST GO-14640 (PI—Pineda). We show a summary of our observations in Table 3. Typically, data were taken using the G140L grating with the FUV-MAMA detector, providing a typical resolving power of ~1000 across 1150–1730 Å. For the brighter targets, we used the echelle grating E140M instead, with similar wavelength coverage and a resolving power of ~45,000. Although the lower resolution of the G140L grating does not permit measurement of the typical FUV line widths, and doublet lines are often blended, our focus in this study is simply the total flux in the strongest FUV lines, which we can measure using G140L for fainter targets than is possible at high resolution using STIS. All observations were taken in photon-counting TIME-TAG mode,
providing high time resolution for our program. We focus on the quiescent emissions of the FUMES sample here, integrated across all exposures and orbits, after removing flares, with the time-resolved analysis to be presented in a follow-up paper.

To extract the spectra from the FUV-MAMA photon-counting detector, we used the \texttt{spectralPhoton} routines from R. O. P. Loyd, previously used in the HST-STIS and HST-COS analyses of M-dwarf UV spectra (e.g., Loyd \\& France 2014; Loyd et al. 2018). To summarize, the reduction procedure sums the photons in a narrow ribbon identified as the stellar trace, subtracting off a background count rate determined from the signal in offset regions with the same wavelengths. The reduction then uses the flux calibration from the full exposures to convert the photon counts to a calibrated spectrum. The advantage of \texttt{spectralPhoton} over the standard output from the STScI pipelines is that it allows for the definition of custom wavelength extraction regions, trace locations, and integrated time intervals. This was important because we found that, for the faint targets LP 55-41 and G 249-11, the standard pipeline products did not correctly identify the stellar trace. Additionally, some of the targets flared during our observations, which we removed by manually identifying when the flares took place and defining custom time intervals during the exposures for extraction of photons corresponding to the quiescent emission spectra.

The majority of our targets were observed in the wider 0′’2 STIS slit, mitigating potential slit-loss effects that could affect the flux calibration by causing poor acquisition, target centering, or guiding. For one target, HIP 23309, observed with the narrower 0′′1 slit for bright object protection considerations, the time series analysis showed a long-term trend in the photon counts over the course of the orbit (this effect was not seen in the data for GJ 410, the other program observation employing the 0′′1 slit). To correct for this, we fit a third-order polynomial to the trend (in the 10 s binned light curve), in order to divide it out, and scaled to the average peak count rate. The quiescent spectrum was subsequently extracted from the appropriately scaled spectrum. For each target, we extracted spectra from each exposure (usually one per orbit) and then co-added them together, rebinning onto a grid of constant linear wavelength. For the echelle spectra, we also merged the wavelength regions in which the echelle orders overlap, averaging flux points falling within the same 0.05 Å bins, and preserving the integrated flux of the spectral bin. We show an example G140L spectrum of one of our targets in Figure 2, and an echelle E140M spectrum in Figure 3.

By using STIS, we were able to observe Lyα in all of our objects, as well as all of the significant FUV emission lines He II λ1640.4 Å, C II λλ1334.5, 1335.7 Å, C III λ1757.7 Å, C IV λ1548.19, 1550.78 Å, Si III λ1206.5 Å, Si IV λλ1393.76, 1402.77 Å, and N V λλ1238.82, 1242.80 Å. These lines span mean formation temperatures $\log T (K) = 4.5–5.2$, probing the transition region of the stellar coronal atmosphere.\footnote{The mean formation temperatures listed in Table 7 depend on the differential emission measure and may differ (significantly) from the peak formation temperature.} We focused on these lines because they are the most prominent ones in the data, being well-measured both in the FUMES targets and the literature sample.

### 3.2. FUV Line Fitting

To measure the target emission line fluxes, we used PyMC3 to fit the observed line shapes, typically with either a Voigt or Gaussian profile convolved with the instrument line spread function.\footnote{The LSFs have spectral resolutions of 1.7–1.5 pixels at FWHM for STIS-G140L and 1.4–1.3 pixels at FWHM for E140M. We used the LSFs obtained from the STScI STIS instrument documentation.} Although we must assume a particular profile shape, these shapes are physically well motivated, and this approach has several advantages over simply summing the flux in the appropriate region for each line. At high resolution, we can measure the line widths, compare the emission core to the line wings, and examine centroid offsets, which are indicative of the stellar radial velocity. We can also simultaneously fit a continuum level below each line and incorporate the uncertainty in that estimate to our reported emission line fluxes. This effect was especially important in the G140L data, where there appeared to be some continuum level below many of the lines. For example, in the region around NV, some of the low-level extended Lyα wing emission could be seen. In the E140M data, no continua were evident. We quantify continuum levels in Section 3.3. Additionally, the line fitting is robust to potentially badly characterized data points, because it allows us to include a fit scatter term to the data in order to account for underestimated errors.

We summarize the model profiles’ fits to the data in Table 4, where the number in front of each profile shape indicates that multiple lines were fit simultaneously, and the continuum component is described by a line with an unknown slope and constant offset. When multiple lines are fit simultaneously, as in the C IV doublet, the widths of the Gaussian and Lorentzian components in the Voigt profile shape are constrained to be identical in each line. This reduces the number of free parameters in the fit, and is justified because each line comes from the same species, forming under similar temperature conditions with only a small difference in energy levels between the transitions. As priors in our Bayesian regression analysis, we used uniform distributions for the line flux, center, and when necessary, the continuum offset and slope. For the width parameters in the Gaussian and Lorentzian components, we used a weakly informative half-Cauchy distribution, with a characteristic width of 100 km s$^{-1}$.$^{12}$\footnote{For the non-negative half-Cauchy distribution, half of the probability mass density is contained at parameter values less than the characteristic width, with the distribution tail decaying in a Lorentzian fashion.} This choice had a negligible effect on the parameter posterior distribution, but

| Name   | UT Date     | Grating | Aperture* | Orbits |
|--------|-------------|---------|-----------|--------|
| GJ 4334| 2017-09-20  | G140L   | 0′′2      | 2      |
| GJ 49  | 2017-09-20  | G140L   | 0′′2      | 2      |
| HIP 112312 | 2017-08-22 | E140M   | 0′′2      | 1      |
| LP 247-13 | 2017-09-13 | G140L   | 0′′2      | 1      |
| HIP 17695| 2017-12-27 | E140M   | 0′′2      | 1      |
| HIP 23309| 2017-11-24 | G140L   | 0′′1      | 1      |
| CD-35 2722 | 2017-09-26 | G140L   | 0′′2      | 1      |
| GJ 410 | 2017-12-18  | G140L   | 0′′1      | 1      |
| LP 55-41 | 2017-09-13 | G140L   | 0′′2      | 3      |
| G 249-11 | 2017-09-10 | G140L   | 0′′2      | 3      |

*Aperture denotes the width of the STIS slit.

\textbf{Note.}

The codes are available on GitHub: \url{https://github.com/parkus/spectralPhoton}.
greatly improved MCMC sampling efficiency and convergence relative to a log uniform prior within PyMC3.

We show examples of our fit line profiles in Figure 4, with the results for the total line fluxes shown in Table 5. The Lyα emission is the focus of Paper II (Youngblood et al. 2021), and we reproduce those results here. For the two targets with E140M data, we fit a single Gaussian line for Si III, to be consistent with the approach for the G140L data, which required simultaneous fitting with Lyα (Youngblood et al. 2021). At the higher resolution, the low-flux C III lines are

Figure 2. FUV spectra of M dwarfs, showing several discrete emission features spanning lines that probe different temperatures in the transition region from C II to N V. This example illustrates a typical spectrum in the FUMES data set (GJ49, \( T_{\text{exp}} = 5585 \) s) spanning 1170–1700 Å, using HST-STIS G140L. Inset figure shows the low-level continuum emission from 1450 to 1520 Å.

Figure 3. HST-STIS E140M data for HIP 17695 (\( T_{\text{exp}} = 1974 \) s), showing the discrete FUV emission features of M dwarfs prominently, with no continuum FUV flux detected. Important emission features are labeled, with the multiplet nature of some of the lines more clearly resolved. Inset figure shows an example continuum emission region from 1570 to 1630 Å.
somewhat blended but distinguishable, so we fit six components to the multiplet but only a single Gaussian feature at low resolution. The He II multiplet, by contrast, remains unresolved in all the data sets, and we fit a single Gaussian for the combined emission accordingly. In general, for the He II line fits, the best model scatter term was often larger than the fits for other lines of the same star, possibly indicating that the shape choice was not ideally suited to the data. For this unresolved multiplet, however, our model choice remains the simplest way to capture the line flux.

For the E140M data, the CII doublet is resolved, but at low resolution the two lines are blended, which impacts the flux measurements because one of the lines is attenuated by ISM absorption. We estimated the typical ISM attenuation of the CII 1334 Å line by assuming typical ISM parameters from Redfield & Linsky (2004) and a stellar line approximated as a Voigt profile with a width of 30 km s^{-1} (0.05 Å) for the Gaussian component and 20 km s^{-1} (0.04 Å) for the Lorentzian component, based on our E140M spectra of HIP 17695's unattenuated CII 1335 Å line. The range of CII ISM parameters identified by Redfield & Linsky (2004) for stars inside 40 pc is 13.1–15.2 for the log column density, 2.9–6.6 km s^{-1} for the Doppler b value, and a radial velocity of −30 to 30 km s^{-1}. We created 10,000 realizations of the attenuated 1334 Å flux, where the column density, b value, and radial velocity of the absorbers relative to the star’s rest frame were drawn from uniform distributions with the ranges described previously. We found that the median attenuation for the 1334 Å line is 14%, with a 68% confidence interval range of 4%–45%. Assuming the 1334 and 1335 Å C II lines are equally

Table 4

| Line ID | G140L | E140M |
|---------|-------|-------|
| Lyα     | Voigt + ISM | Voigt + ISM |
| He II   | Gaussian + Continuum | Gaussian |
| C II^b  | Gaussian + Continuum | Voigt |
| C III   | Gaussian + Continuum | 6x Gaussian |
| C IV    | 2x Voigt + Continuum | 2x Voigt |
| N V     | 2x Voigt + Continuum | 2x Voigt |
| Si III^a| Gaussian + Lyo | Gaussian |
| Si IV   | 2x Voigt + Continuum | 2x Voigt |

Notes.

^a For G140L data, the Lyα line is jointly fit, accounting for ISM absorption, with Si III (Youngblood et al. 2021), but for E140M data, the Si III line is fit independently.

^b For the E140M data, we fit only the single redward line in the C II doublet, λ 1335.71 Å, since the λ 1334.54 Å line is affected by the ISM; for G140L data, these lines are blended (see Table 5).

somewhat blended but distinguishable, so we fit six components to the multiplet but only a single Gaussian feature at low resolution. The He II multiplet, by contrast, remains unresolved in all the data sets, and we fit a single Gaussian for the combined emission accordingly. In general, for the He II line fits, the best model scatter term was often larger than the fits for other lines of the same star, possibly indicating that the shape choice was not ideally suited to the data. For this unresolved multiplet, however, our model choice remains the simplest way to capture the line flux.

For the E140M data, the C II doublet is resolved, but at low resolution the two lines are blended, which impacts the flux measurements because one of the lines is attenuated by ISM absorption. We estimated the typical ISM attenuation of the C II 1334 Å line by assuming typical ISM parameters from Redfield & Linsky (2004) and a stellar line approximated as a Voigt profile with a width of 30 km s^{-1} (0.05 Å) for the Gaussian component and 20 km s^{-1} (0.04 Å) for the Lorentzian component, based on our E140M spectra of HIP 17695’s unattenuated C II 1335 Å line. The range of C II ISM parameters identified by Redfield & Linsky (2004) for stars inside 40 pc is 13.1–15.2 for the log column density, 2.9–6.6 km s^{-1} for the Doppler b value, and a radial velocity of −30 to 30 km s^{-1}. We created 10,000 realizations of the attenuated 1334 Å flux, where the column density, b value, and radial velocity of the absorbers relative to the star’s rest frame were drawn from uniform distributions with the ranges described previously. We found that the median attenuation for the 1334 Å line is 14%, with a 68% confidence interval range of 4%–45%. Assuming the 1334 and 1335 Å C II lines are equally
emission lines were barely visible. We determined the 3σ lines are blended should be corrected upward the blended doublet, including ISM absorption. We estimate that these measurements should be corrected upward by poorly characterized uncertainties, and thus these values should be taken with

The STIS data for G249-11 and LP 55-41 were much fainter the central 68% confidence interval about the median.

FUV Continuum Measurements

| Name      | Obs Flux (erg s⁻¹ cm⁻² Å⁻¹) | S/N |
|-----------|-------------------------------|-----|
| GJ 4334   | 5.5 ± 0.3 × 10⁻¹⁷            | 18  |
| GJ 49     | 7.4 ± 0.3 × 10⁻¹⁷            | 25  |
| HIP 112312| 5.8 ± 0.8 × 10⁻¹⁶            | 7.25|
| LP 247-13 | 1.7 ± 0.05 × 10⁻¹⁶           | 34  |
| HIP 17695 | 3.3 ± 0.4 × 10⁻¹⁶            | 8.25|
| HIP 23309 | 3.10 ± 0.09 × 10⁻¹⁶          | 34  |
| CD-35 2722| 1.91 ± 0.05 × 10⁻¹⁶          | 38  |
| GJ 410    | 1.3 ± 0.1 × 10⁻¹⁶            | 13  |
| LP 55-41  | 0.06 ± 1 × 10⁻¹⁸             | ... |
| GJ 249-11 | 5 ± 6 × 10⁻¹⁹                | ... |

Note.

The E140M spectra show very little continuum, if any, leading to likely poorly characterized uncertainties, and thus these values should be taken with caution.

The STIS data for G249-11 and LP 55-41 were much fainter than the rest of the FUMES targets, and many of the typical emission lines were barely visible. We determined the 3σ upper limits for these lines by simply summing the flux in the region around the expected line center and computing the associated uncertainty in that flux. For the few lines that were measurable (C II, C IV, and N V), we accommodated the lower S/N by only fitting single Gaussian line profiles in each case, one component for the blended C II, and two components each for the C IV and N V doublets. These results are included in Table 5.

3.3. FUV Continuum Emission

Although the FUV spectra of low-mass stars is dominated by discrete emission-line features, there is a weak underlying FUV continuum that is likely defined by the recombination edges of species like Si (Loyd et al. 2016; Peacock et al. 2019). As seen in Figures 2 and 3, continuum emission between the strong line features was evident in the low-resolution G140L spectra, but not apparent in the high-resolution E140M spectra. This is a consequence of the higher sensitivity and lower resolution of the G140L grating, making it easier to detect weak continuum levels. Compared to HST-COS medium-resolution gratings (G130M, G160M), the HST-STIS low-resolution grating (G140L) is slightly more sensitive at detecting faint continuum emission.13 For the full FUMES sample, we quantify the FUV continuum levels apparent in our spectra following the work of Loyd et al. (2016).

As part of the MUSCLES program, they defined an ensemble of narrow bands (0.7–1 Å in width) interspersed between the prominent FUV emission lines, to assess the FUV continuum flux across 1300–1700 Å. We used these same bands (obtained from R. O. P. Loyd 2021, private communication) transformed to the radial velocity frame of our targets, to integrate the FUV continuum.14 We were able to use the bands unaltered for the E140M data sets; however, for the lower-resolution G140L data, we visually verified that the bands did not overlap with any of the strong emission lines. This removed six narrow bands (~6 Å) that encompassed parts of emission-line wings.

The integrated fluxes in these narrow bands are shown in Table 6, averaged over the ~150 Å cumulative width of the passbands. For eight of the ten targets, including the two observed with the E140M grating, we measure a nonzero FUV continuum level, all except for G149-11 and LP 55-41. Although the integrated flux is usually insignificant in each narrow band, revealing no clear continuum shape, when adding
up the emissions across all of the narrow passbands of the spectra, the overall continuum emission is detectable. For the quoted uncertainties of Table 6, we propagated the data uncertainty through the continuum flux summation.

Our results are broadly consistent with those of Loyd et al. (2016), accounting for the distance to each target; however, with this broader sample of stars, we see evidence for a wide array of continuum levels. Spectra with higher S/Ns are needed in order to verify the detection of these average continua and determine what defines their flux levels and spectral composition.

3.4. Line–Line Correlations

Our FUV emission line measurements are diagnostic of the stellar upper atmospheres and how they change with magnetic heating. Because they form in similar regions, the line strengths are strongly correlated, as has been well-illustrated in the literature (e.g., Youngblood et al. 2017). We build on these results by expanding the available UV samples using our new measurements with the FUMES targets. In addition to the FUMES data, we also analyzed the Mg II NUV data for the literature sample, as representative of an additional atmospheric layer and the spectral region of interest.

Since C IV is a bright and readily accessible emission feature, we show in Figures 5–6 the correlation of each of the emission lines of Table 5 against C IV. We plot the luminosities of each feature as two-dimensional error ellipses (2σ contours) representative of the bivariate error distributions for the luminosities of each line pair. We further discuss the differences in undertaking this analysis in luminosity as compared to surface flux in Appendix A.1. Since each luminosity depends on the known parallax and its uncertainty, the luminosity determinations have correlated uncertainties, revealed by diagonally oriented ellipses. This correlation is more prominent when the parallax uncertainty dominates the luminosity measurements. Figures 5 and 6 show these data.

![Figure 5. Our FUV emission line correlations for the combined FUMES (black outline) and literature samples show tight power-law fits, \( L_\gamma = C L_{CIV} \), with scatter \( s \). Each star is shown as a representative error ellipse corresponding to a 2σ confidence level. Dashed lines show the individual best-fit relations for each line pair. Any FUV line can be used to predict any other emission line in quiescence. Lower panel of each plot shows the central residuals from the power-law fit, with the intrinsic scatter shaded in gray.](image-url)
with the filled shading of each shape indicating the effective temperature of the stars. The emission fluxes are not primarily determined by the stellar effective temperature, as both warmer and cooler objects in the FUMES and literature samples show high and low FUV luminosities, but instead by each object’s activity regime, as will be discussed in Section 4.

The correlations shown in Figures 5–6 further demonstrate that the C\textsc{iv} strength can be used to predict the quiescent emission of any of the other prominent transition region emission lines across four orders of magnitude in luminosity. To these data, we fit a power-law relation, using C\textsc{iv} as the predictor variable, within a Bayesian framework (Kelly 2007), accounting for uncertainties in both dimensions and incorporating an intrinsic scatter at fixed C\textsc{iv} luminosity. We defined the regression model for the line luminosities, $L_y$, as

$$
\log L_{\gamma|C} \sim N(\gamma \log L_{\text{CIV}} + \log C, s),
$$

where $x$ corresponds to C\textsc{iv} and $y$ any of the other lines (e.g., N\textsc{v}, Si\textsc{iv} etc.), $N(\mu, \sigma)$ denotes a normal distribution of mean $\mu$ and standard deviation $\sigma$, $i$ denotes each star in the data set, and $s$ is the intrinsic scatter of the power-law relation in log–log space.\(^{15}\) The $s$ parameter is fit along with the power-law model, with its marginalized posterior distribution describing the set of intrinsic scatters consistent with the uncertainty of the data and the posterior distributions on $\gamma$ and $C$. The peak of that distribution is our best estimate of the representative intrinsic scatter in the line–line correlations. As an example, a scatter value $s = 0.1$ would suggest that an individual line luminosity could be predicted to within $\sim 25\%$, corresponding to the central 68% confidence interval, with a known C\textsc{iv} luminosity.

The probability distributions for each line luminosity pair were defined, in the case of FUMES targets, by their joint distribution created from the sampled line flux posteriors of the model fits (see Section 3.2) combined with the parallax measurement and its uncertainty. For literature data, we assumed Gaussian distributions for the line fluxes and

\(^{15}\) The notation of Equation (1), e.g., $z\mid u, w \sim N(u, w)$, indicates that the random variable $z$ conditioned on $u$ and $w$ follows the probability density function defined by $N$.\(^{15}\)
combined with the parallax measurements to determine the joint luminosity distributions at each pair of data. The likelihood is defined by the product across the sample of stars with Equation (1). In log–log space, this is a linear model, and we used a uniform prior on log $C$, the offset, a Cauchy distribution for the power-law exponent, $\gamma$, and a half-Cauchy distribution with unity shape parameter for the scatter, $s$. These priors are minimally informative, and only marginally affect the posterior distributions in $\gamma$, $s$, and $C$, while improving Monte Carlo convergence efficiency. An example of the joint posterior distributions for these fits is shown in Figure 7. The results of these fits are indicated by the dashed lines in Figures 5–6, and we tabulate the fit parameters in Table 7.

The line pair with the smallest intrinsic scatter is CIV–N V ($\sim$0.1 dex). This is unsurprising, as these two lines are optically thin and form at similar temperatures high in the transition region. We thus considered whether there may be a trend in intrinsic scatter relative to the temperature of line formation (see Table 7). The data do not reveal any suggestive trends, although Mg II and Ly$\alpha$ show the greatest scatter values and correspond to the lines with the lowest formation temperatures of those that we studied. On the contrary, C II forms at temperatures similar to those of Mg II and shows as small a scatter as the hotter Si IV transition region line. The larger scatter for Mg II relation could be due to unaccounted for uncertainty associated with the ISM correction needed for the Mg II flux estimates (Youngblood et al. 2016). This may also affect the Ly$\alpha$ correlation; however, the formation of Ly$\alpha$, its central profile, and its broad emission (Youngblood et al. 2021) are likely more complicated (Peacock et al. 2019). Therefore, predicting the emission from the transition region C IV luminosity may not account for all of the processes impacting the Ly$\alpha$ flux.

The rest of the line–line correlations show consistent scatters of 0.1–0.2 dex at fixed C IV luminosity. These measurements represent the intrinsic scatter of FUV line emission across the population, as all of the observations were either taken simultaneously or closely spaced in time (Franche et al. 2016). If this is indeed due to intrinsic variation, it may define the limit to which FUV features can be used to predict one another. Additionally, this intrinsic variation may differ between the “inactive” and “active” subsamples; however, our samples in each are not large enough to fully investigate.

4. Rotation–Activity Relation

4.1. Regression Model Fitting

Canonical rotation–activity correlations with optical and X-ray emission (e.g., Pizzolato et al. 2003; Wright et al. 2011; Astudillo-Defru et al. 2017; Newton et al. 2017) have illustrated a strong rotational dependence, typically characterized by a power-law distribution, and a saturated regime of activity for the fastest rotators. Since Noyes et al. (1984), these relationships have been used to investigate the interplay between the internal convective motions and differential stellar rotation within an $\alpha$–$\Omega$ magnetic dynamo, thought to operate in stars with partly convective interiors (e.g., Montesinos et al. 2001; Browning et al. 2006). Mediated by the tachocline interface between the radiative core and convective envelope, the dynamo sustains the magnetic field through cyclic regeneration of toroidal and poloidal field. Theory suggests that the magnetic fields—and hence the resulting activity tracers—should thus be mediated by the Rossby number, $Ro = P/\tau_v$, the ratio between the rotational period and the convective turnover time, which characterizes the timescales for bulk motions of internal convection. Recent results have further extended these studies across the boundary between fully convective and partly convective interiors (Newton et al. 2017; Wright et al. 2018), with M-dwarf samples illustrating a
We discuss systematic effects of this choice of calibration in the scatter term, a function of $\log \tau_o$:

$$L_y/L_{bol} = \begin{cases} (L_y/L_{bol})_{sat}, & \text{if } \tau_o \leq \tau_c, \\ A(\log \tau_o)^{-\eta}, & \text{if } \tau_o > \tau_c, \end{cases}$$

(2)

where $(L_y/L_{bol})_{sat}$ denotes the strength of emission line, $y$, in the saturated regime relative to the star’s bolometric luminosity, $\eta$ indicates the slope of the unsaturated regime, and $\tau_c$ is the critical Rossby number at which the activity transitions between regimes, with $A \equiv (L_y/L_{bol})_{sat}(\tau_c)^{-\eta}$ to ensure continuity. To compute the Rossby number, we use the known rotation periods (see Table 2) and the empirical calibration for the convective turnover time, $\tau_c$, as a function of mass from Wright et al. (2018).

We further consider the quality of our estimates for determining $\tau_c$ by using the known rotation periods. Within this Bayesian model, we employ as priors uniform distributions for $\log(L_y/L_{bol})_{sat}$ and $\tau_c$, a zero-centered Cauchy distribution with unity shape parameter for the slope $\eta$ (see footnote 17), and a half-Cauchy distribution with unity shape parameter for $\sigma_{\tau_c}$.

Our fitting process using PyMC3 accounts for random uncertainty in both dimensions (Kelly 2007), and possible error correlations between the assumed mass and bolometric luminosity using the sampled posterior distributions from the work of J.S. Pineda et al. (2021, in preparation). The error correlations between $M$ and $L_{bol}$ are generally small for the field objects, but can be significant for the young stars (see J.S. Pineda et al. 2021, in preparation). We also included the scatter in the convective turnover time calibration from Wright et al. (2018) of 0.055 dex in $\log \tau_c$ at fixed mass. When using the literature periods, we further incorporated the quoted uncertainties in those measurements if available, or used a 10% Gaussian uncertainty if not; see Table 2 (E. Newton 2020, private communication). Except for the Lyα measurements of some stars, the random uncertainties in the rotation–activity relation data are typically dominated by the error on the Rossby number driven by the scatter in the $\tau_c$ calibration. This careful accounting of the known sources of random error enabled us to carefully examine systematic effects with this fitting (see Appendix A.2).

We applied these methods to eight UV emission lines, Lyα, Mg II, C II, Si III, He II, Si IV, C IV, and N V, for which the samples permitted a detailed rotation–activity fit. We show the best parameter results from the marginalized posteriors in Table 8, with the fit solutions plotted in Figure 8. We also show an example of the joint posterior distributions for this fitting in Figure 9, illustrating how the critical Rossby number and unsaturated regime slope are generally correlated in our rotation–activity parameterization of Equation (2).

Because this regression analysis relies on stellar mass estimates for determining $\tau_c$, it may be potentially biased by our choice for the young stars to utilize the magnetic-model-based masses, which are larger than the non-magnetic-model masses (see J.S. Pineda et al. 2021, in preparation), with a correspondingly larger implied $\tau_c$. This concern applies only to the five young stars in our sample (see Table 2). However, of the five, only AU Mic ($\tau_c = 0.11 - 0.17$) appears to be near the transition between saturated and unsaturated regimes. HIP 112312, HIP 17695, and CD-35 2722 have $\tau_c$ values well below 0.1 regardless of the model choice for the mass estimate, and HIP 23309 has an $\tau_c = 0.32 - 0.39$, larger than the literature values of $\tau_c \sim 0.15 - 0.20$ (Newton et al. 2017; Wright et al. 2018). Because horizontal systematics within the saturated regime have no influence on the rotation–activity fits, and only one of the stars in a sample of $\gtrsim 20$ targets per emission line might be affecting the analysis, we consider this systematic effect in young star masses to minimally impact our results. Furthermore, these young stars do not appear to be outliers in our rotation–activity plots (Figure 8). Although the difference in $\tau_c$ is small, only the result for Mg II is likely to be impacted by the mass choice for AU Mic, because of the limited target sample for that line. Correspondingly, the rotation–activity fit parameters for Mg II have larger uncertainties.

We further consider the quality of our fits by examining the residuals, as illustrated in Figure 10. The data residuals are consistent with being normally distributed about the best median rotation–activity relation, and they show no apparent dependence on stellar mass. There may be some hints of an

| Line | $N_{samp}$ | $\eta$ | $\log(L_y/L_{bol})_{sat}$ | $\log(L_y/L_{bol})(\tau_c)^{-\eta}$ | $\sigma_{\tau_c}$ |
|------|------------|--------|---------------------------|-------------------------------------|------------------|
| Lyα  | 19         | -1.26±0.41 | 0.21±0.16 | -3.58±0.13 | 0.32±0.07 |
| Mg II| 12         | -1.86±0.41 | 0.20±0.11 | -3.99±0.14 | 0.23±0.07 |
| C II | 15         | -2.38±0.77 | 0.24±0.12 | -5.25±0.16 | 0.33±0.07 |
| Si III| 20       | -2.08±0.44 | 0.20±0.07 | -5.37±0.13 | 0.32±0.06 |
| He II| 24         | -2.19±0.33 | 0.19±0.05 | -4.92±0.11 | 0.27±0.04 |
| Si IV| 21         | -2.32±0.46 | 0.24±0.07 | -5.38±0.14 | 0.35±0.06 |
| C IV | 24         | -2.02±0.39 | 0.18±0.06 | -4.72±0.15 | 0.37±0.06 |
| N V  | 23         | -1.84±0.40 | 0.19±0.07 | -5.37±0.14 | 0.33±0.07 |

Note.

* Reported parameters correspond to the median of the marginalized posterior distribution, with uncertainties indicating the central 68% confidence interval.
excess of data points below the median fit at large Rossby numbers (∼1), but this sample is too small to be conclusive in this regard. This may be more evident in literature studies (e.g., Newton et al. 2017), which would indicate that, at slow rotation periods, the single power law may be overestimating the magnetic activity.

With these considerations, for all of the emission lines, we deem the broken power law to accurately describe the rotation

Figure 8. Rotation–activity correlations are prominent across all of the UV emission features analyzed in this work. Individual data points are represented by 1σ error ellipses, shaded to indicate each star’s effective temperature. Best-fit broken power-law models (see Section 4) are shown in gray, illustrating the 1σ (dark gray) and 2σ (light gray) scatters.
the correlation of the slope broken power-law indicating the same scatter value, regions of top panel are as in Figure 8, with dotted line in lower panel shown in Table 8.

Residuals are consistent with a normal distribution, and they show no example, but now with error ellipses shaded according to stellar mass. sample for each emission line, with the results for NV shown here again as an example, but now with error ellipses shaded according to stellar mass. sample, with each line showing slightly different emissions levels in the saturated regime, consistent critical Rossby values of $\sim 0.2$, and a range of slopes in the unsaturated regime spanning $-1.3$ to $-2.4$ (see Table 8). For our M-dwarf sample, the saturation levels of $\log (L_{\text{line}} / L_{\text{bol}})_{\text{sat}}$ in the C II, Si III, N V, and Si IV lines all exceed those measured by France et al. (2018) for an ensemble of FGKM stars, which were all in the range of $-5.5$ to $-6$. In the saturated activity regime, M-dwarf FUV emissions exceed those of warmer stars, relative to bolometric. For the power-law decay with decreasing rotation, all the lines except Ly$\alpha$ are consistent with a slope of $-2$, with Ly$\alpha$ corresponding to the shallowest slope in the rotation--activity analysis. While the error bar is large, because these data rely on model reconstructions of the emission flux, we consider whether those assumptions may be systematically impacting this result.

4.2. Ly$\alpha$ and Evolving Emission-line Ratios

Our Ly$\alpha$ reconstructions (Youngblood et al. 2021) and those from the literature sample (Youngblood et al. 2016), typically assume a Voigt-like profile for the emission; however, some evidence and theory exist that suggest the ISM-obscured Ly$\alpha$ profile peak may show an absorption self-reversal like that observed in other chromospheric lines (e.g., Linsky et al. 1979; Redfield & Linsky 2002; Guinan et al. 2016; Youngblood et al. 2016; Peacock et al. 2019). Our Ly$\alpha$ reconstructions do not account for this effect, therefore we may be overestimating the Ly$\alpha$ flux. However, for this effect to impact the fitted slope in the rotation--activity unsaturated regime, the strength of self-reversals would also need to depend on the Rossby number. Theoretical Ly$\alpha$ line profiles from Peacock et al. (2019) for GJ 832, GJ 176, and GJ 436 also show strong core absorption due to non-LTE effects, such that the reconstructed fluxes are greater by a factor of $\sim 2$. A systematic effect at this level or stronger between active and inactive M-dwarfs is needed to explain the shallow Ly$\alpha$ slope. However, more data are required in order to validate whether these theoretical profiles match those produced by nature. There is currently no evidence for such a systematic difference in Ly$\alpha$ core profiles between active and inactive M dwarfs.

If typical Ly$\alpha$ lines only show weak self-reversals in M dwarfs, as suggested empirically by Guinan et al. (2016) and Bourrier et al. (2017), then the shallow slope could indicate the persistence of Ly$\alpha$ emission at slow rotation rates even as other high-energy features decay more rapidly. As they are most prominent emission lines in the FUV and NUV, respectively, we consider the evolution of the ratio of Ly$\alpha$ to Mg II emissions. We illustrate this in Figure 11, showing the emission ratio as a function of Rossby number. The shaded region denotes the ratio of the power-law fits in the two lines from Section 4.1 consistent with the uncertainties in the parameter estimates to the $1\sigma$ level. More data are needed to better refine rotation--activity relationships in both features, but the rise in ratio with angular momentum evolution indicates that the relative strengths of different portions of the high-energy spectrum changes over time. Evolutionary changes in the spectral illumination have implications for the prevalent photochemistry and atmospheric history of any exoplanetary systems orbiting low-mass hosts. For example, stronger FUV relative to NUV emissions may drive a build-up of photochemical ozone in planetary atmospheres (e.g., Gao et al. 2015: Harman et al. 2015). Although a full account of the relative contribution of Mg II to the total NUV luminosity is necessary for a complete description, our data suggest that this effect may increases as stars spin down over time. Furthermore, such an evolutionary effect may be more prominent for early-M dwarfs.
but not as significant for late-M dwarfs (Schneider & Shkolnik 2018).

4.3. Trends with Formation Temperature

Our results across all of the lines (Table 8) reveal that most of the best-fit slopes are around the canonical value of $-2$ implied by a distributed dynamo model (Noyes et al. 1984) in which dynamo amplification occurs throughout the convective region. By contrast, in an interface dynamo like that based on a tachocline, there are additional dependencies that lead to deviations away from this canonical slope of $-2$ (Parker 1993; Charbonneau & MacGregor 1997; Wright et al. 2011). To compare these results from the different lines, we plot our fit parameters for $\eta$ and $R_{\text{c}}$ as a function of line formation temperature in Figure 12. The UV lines are plotted at the temperatures listed in Table 7, to which we also add the Hα results of Newton et al. (2017) as representative of the chromosphere, and the X-ray results of Wright et al. (2011, 2018) corresponding to the corona using a nominal temperature of $10^6$ K, although X-ray flux contributions extend to higher temperatures. In Figure 12, we show the mean value representative of the transition region, taking the combined posteriors across all the lines in each parameter, yielding medians and central 68% confidence intervals of $\eta = -2.02^{+0.55}_{-0.55}$ and $R_{\text{c}} = 0.20^{+0.09}_{-0.07}$. Our mean result is consistent to within the uncertainties with both the chromospheric and coronal results in the literature.

However, there may be a trend in the unsaturated rotation–activity slope as a function of formation temperature. While this is largely a consequence of different values for the Hα and X-ray results, our UV data fall directly in between. As stars spin down in the unsaturated regime, the coronal X-ray emissions appear to decline rapidly, with deeper atmospheric layers showing a slower decay in their magnetic activity. The onset of activity decline with slower rotation begins first in X-rays, and only after some angular momentum evolution do the transition region and chromospheric features also begin to decline, as the best-fit $R_{\text{c}}$ are greater for the deeper layers.

If these trends hold from analyses of larger UV samples, they will help reveal the role of magnetic heating processes in mediating the relationship between the internal magnetic dynamo and the emission features. While the rotation–activity relationships have been used to constrain stellar dynamos, this connection is indirect. The emission is necessarily a consequence of the nonthermal magnetic heating, and if the different layers exhibit distinct power-law slopes, then this effect of the heating processes needs to be accounted for when making dynamo inferences from rotation–activity relationships. The trend evident in the top panel of Figure 12 for the unsaturated slope suggests that, whether the dominant process is Alfvén wave heating or nanoflare reconnection, the decline in nonthermal heating with weaker average field strengths (e.g., Shulyak et al. 2017) as stars spin down takes place from the outermost layers inward. In other words, the magnetic heating processes persist more strongly in deeper atmospheric layers across angular momentum evolution, affecting the relative strengths of emission features formed in different layers of the atmosphere.

There are, however, some important caveats to the comparisons implicit in Figure 12. Between this work and the studies of Newton et al. (2017) and Wright et al. (2011, 2018), the samples are not identical. Our work and that of Newton et al. (2017) use...
similar mixed-age samples of M dwarfs, whereas the X-ray data of Wright et al. (2018) also include more massive stars, although normalizing by the bolometric luminosity and examining the rotation relationship in Ro is designed to account for these possible differences. More significantly, as we discuss in Appendix A.2, differences in the Ro calibration can impart systematic effects on the rotation–activity analyses. Newton et al. (2017) used the calibration of Wright et al. (2011), whereas we used that of Wright et al. (2018). Relative to our work, the Newton et al. (2017) results for critical Rossby number and unsaturated slope could be systematically greater than if they used the same calibration. The magnitude of this effect, however, can be small, and it depends on the stellar sample (see Appendix A.2). Moreover, there may have been issues with the analyses of Wright et al. (2011) leading to a much steeper power-law slope (Reiners et al. 2014). Nevertheless, it appears that, in the chromosphere, $\eta$ is likely shallower than $-2$, whereas in the corona, it is steeper than $-2$, with the transition region value from our work right in the middle. Consistent methods and calibrations need to be applied across the different wave bands, to discern whether there are indeed rotation–activity trends as a function of where in the stellar atmosphere the emission originates.

4.4. Alternatives to Rossby Number?

Potential issues with a choice of calibration can be avoided by circumventing the Rossby number entirely. Reiners et al. (2014) argue for a more general approach in analyzing the rotation–activity relationships of low-mass stars, and conclude that the activity dependence can be described well by a combination of rotation period and radius, specifically $L_X/L_{bol} = kP^{-2}R^{-4}$, where $k$ is a scaling constant. We consider how this relationship may apply to our UV data. In Figure 13, we show the He II luminosity normalized by stellar bolometric luminosity against the stellar $P^{-2}R^{-4}$. Like the Rossby scaling, Figure 13 illustrates a potentially power-law decay in emission with a scatter of activity at a given abscissa. Although our sample is much smaller, there are hints of the mass dependence in activity using this scaling that was illustrated by Newton et al. (2017) with Hα data, in which more massive stars preferentially lie to the right of the locus of points in Figure 13.

The mass dependence appears to increase the intrinsic scatter at fixed rotation in the activity beyond the $\sim 0.27$ dex scatter evident in our fits to $L_{He\ II}/L_{bol}$ versus Ro.

While it is evident that rotation still plays a key role in the magnetic emission of fully convective stars, an empirical Rossby number may not be the most appropriate scaling to uncover the underlying relationships governing the dynamo action and possible differences from partly convective stars. It appears to work sufficiently well across the chromosphere, transition region, and corona; however, by defining Ro specifically to minimize scatter in the rotation–activity diagrams across this full range of stars, this procedure may be masking real differences in the evolution of magnetic activity between partly and fully convective objects (e.g., Magauada et al. 2020). If these two stellar mass regimes did indeed show distinct rotation–activity correlations, i.e., statistically distinguishable rotational dependencies of their activity decay, the process of defining an empirical Rossby number across both samples would be averaging together these possible differences, since it presupposes that both samples follow the same power-law relation.

5. Temporal Evolution

In Section 4, we used the stellar rotation period as a proxy for examining magnetic activity throughout the lifetimes of low-mass stars. However, using gyrochronology (e.g., Barnes 2003), we can also compare our FUV activity indicators directly to stellar ages using literature relations connecting rotation period and age. While this practice is well-established for Sun-like stars (e.g., Angus et al. 2015; Gallet & Bouvier 2015), the process is much more difficult for M dwarfs (e.g., Guinan et al. 2016), which lack a multitude of targets with well-determined ages. Nevertheless, Engle & Guinan (2018) have developed empirical relations for M0–M1 and M2.5–M6 dwarfs, to estimate ages from measured rotation periods. Although work to explore such gyrochronology relations for M dwarfs remains ongoing, we use those results in this paper in order to provide an approximate indication of the expected behavior across the low-mass star regime.

5.1. UV Emissions across Time

We thus show the evolution of FUV activity with age in Figure 14, focusing on the N V emission feature as representative of all of the other FUV lines (Sections 3.4 and 4). We chose the N V line for this analysis because it is tightly correlated with C IV, and existing literature relations allow us to also estimate EUV emission from their measurements; see below.

For the five objects with moving group membership (see Table 2), we used the mean group age with error, and we used the gyrochronology relations for the rest of the sample. To assess the uncertainties on the ages from the gyrochronology calibration, we used the reported uncertainties of the parameters of the best-fit relations (Engle & Guinan 2018) and the period uncertainties as in Section 4.1, sampling each appropriately, assuming independently Gaussian distributed variables in computing the distribution for the age estimate. Because the Engle & Guinan (2018) rotation–age relations are
defined by two bins of spectral type ranges, for our sample, we used the appropriate relation corresponding to the optical spectral types listed in Table 2. However, some of our objects have spectral types, M1.5-M2, between the defined ranges for the rotation–age relations. For these objects, we combined the estimates from both the M0–M1 and M2.5–M6 relations in order to determine the age estimate and its uncertainty. Three of these stars were rapid rotators without known ages: AD Leo, EV Lac, and LP 247-13. Given the large uncertainty in the gyrochronology ages—especially early on, where the rotational evolution has yet to converge—we plot these age estimates as 3σ upper limits (triangles in Figure 14).

In Figure 14, we also shade the points according to their effective temperature. Based on these age estimates, Figure 14 illustrates how cooler, later M dwarfs persist with strong activity levels for a longer duration of their early lifetimes. Considering the mean level of log(L_NV/L_Bol)_sat ~ -5.37 and 0.33 dex scatter, some of the cooler objects may display near-saturation-level activity beyond an age of 1 Gyr. In contrast, the warmer M dwarfs, by this age, appear to have declined in their magnetic emissions by an order of magnitude relative to the saturated regime. Using GALEX photometry, Schneider & Shkolnik (2018) also found this divergence in UV evolution between early- and mid-M dwarfs.

Because of its importance to exoplanetary atmospheric heating, we also considered what our FUV evolutionary data imply for the extreme ultraviolet portion of the high-energy spectrum. To estimate the EUV from the FUV data, we used the empirical relation of France et al. (2018) between N V emission and the blue portion of the EUV passband, EUVb (90–360 Å). While not the full EUV spectrum, this is the portion for which available data and relatively low ISM attenuation have permitted any empirical estimates in the low-mass star regime. This EUVb band corresponds to about half of the total EUV energy from M-dwarf stars (Fontenla et al. 2016; France et al. 2018). In Figure 15, we plot this EUV evolution with the same ages as discussed above, and EUVb luminosities determined from the N V emission, incorporating the parameter uncertainties and 0.24 dex scatter in the France et al. (2018) relation. For young, active, M-dwarf stars, the EUV luminosity is ~10^{-3.5} relative to bolometric, with these emissions lasting for the first several hundreds of Myr of their lives—and perhaps longer.

While these empirical relations for age, and difficult-to-detect portions of the spectrum, like the EUV, provide general estimates for the evolution of activity and high-energy emission, Figure 15 further illustrates the broad uncertainty inherent in using these estimates as inputs to exoplanetary evolution modeling. Refined rotation–age relations in the M-dwarf regime, and expanded samples of stellar EUV detections from missions like ESCAPE (France et al. 2019), will greatly expand the utility of these methods for exoplanetary applications.

Assuming the Rossby parameterization removes a significant mass dependence, we use the rotation–activity correlation regression fits together with the assumed rotation evolution in order to calculate the activity evolution of early- and mid-M dwarfs. In Figure 16, we plot separate curves for the evolution of N V emission with stellar age, for a 0.6 M_\odot M dwarf, corresponding to the M0–M1 rotational evolution, and a 0.25 M_\odot M dwarf, corresponding to the M2.5–M6 rotational evolution. The top panel of Figure 16 shows the expected median evolution for each mass star along with its central 68% confidence level. The uncertainties are determined at a given age by sampling the uncertainty distributions of the rotation–age relation, the calibration between mass and convective turn over time, and the joint posterior of the rotation–activity fit. The bottom panel of Figure 10 additionally includes the scatter at fixed Rossby number (see Section 4), to illustrate the range of likely emission values accounting for intrinsic scatter in the observed population. More data are required for further assessment; however, we expect this scatter to include the effects of rotational variability, activity cycles, and possible metallicity variations. While the nominal N V emission levels relative to bolometric are higher for lower-mass objects at the same age, there is little difference in the evolution within the uncertainties.

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**Figure 14.** N V luminosity of our sample as a function of age illustrates how young M stars exhibit saturated FUV emissions that last for ~1 Gyr before declining. Cooler M dwarfs also show strong UV emissions for longer into their lifetimes than warmer objects. Age uncertainties (\sigma) are determined from the group age determination in the literature, or from the uncertainties in the gyrochronology relations, with upper limits for the rapid rotation star ages indicated as triangles; see Section 5.

**Figure 15.** Based on available scaling relations from the FUV (France et al. 2018), we can estimate the EUVb (90-360 Å) luminosity of low-mass stars, similar to Figure 14. Temporal evolution of EUV emission drops ~2 orders of magnitude from youth to field ages; see Section 5.
accompanied by the observed scatter across the populations at different ages, because we focus here on the cumulative average evolution. Bottom panel includes the likely range for emission, accounting for the observed scatter across the populations (≈0.33 dex).

5.2. Accumulated UV Evolutionary Histories

With possibly distinct UV luminosity evolution between early- and mid-M dwarfs, as shown in Figure 16, we calculate the typical evolution of the UV illumination for exoplanetary systems using the median N V rotation–activity relation (Section 4), and the age–rotation evolution from (Engle & Guinan 2018). The average evolution for individual systems may vary by up to a factor of two. As a measure of the illumination histories, we assess how much quiescent UV energy a given exoplanet accumulates over time as

$$\mathcal{E}(t) = \int_0^t F_{\text{UV}}(\tau) d\tau = \int_0^t \frac{\mathcal{R}(\tau)L_{\text{bol}}(\tau)}{4\pi d^2} d\tau,$$  \hspace{1cm} (4)

where $F$ is the UV flux impinging on the planet at an average distance $d$ from the host, and we integrate from 0 to an age $t$. The UV flux can be rewritten as a combination of the emission ratio evolution, $\mathcal{R}(\tau) = L_{\nu}/L_{\text{bol}}$, determined from Section 4, and $L_{\text{bol}}(\tau)$, which accounts for changes in bolometric luminosity with stellar evolution. In evaluating Equation (4), we use evolutionary models (Dotter et al. 2008; Feiden 2016) for the bolometric luminosity, which can evolve substantially at young ages (see Figure 17) and allows a self-consistent metric across several Gyr. We compared the accumulated UV energies for planets around a 0.25 $M_\odot$ host and a 0.60 $M_\odot$ host with that of a planet around a Sun-like star.

In order to compare with the lower-mass objects, the UV emission history for Sun-like stars required a treatment different from our approach with M dwarfs. Using a sample of G dwarfs, Ribas et al. (2005) determined the EUV evolutionary history of Sun-like stars as a simple power-law decay with time across 0.1–6.7 Gyr. Since results from France et al. (2018) suggest that the N V emission and EUV of solar- and lower-mass stars are related by a simple multiplicative factor, we consider the Sun-like N V emission to follow the same power-law defined by Ribas et al. (2005). We thus scaled their result to the Sun’s current N V luminosity from Duvvuri et al. (2021) using the solar minimum quiescent solar irradiance spectrum of Woods et al. (2009):

$$F_{\text{N}\text{V},\odot} = 0.105 \tau^{-1.23}, \text{erg s}^{-1} \text{cm}^{-2}, \quad 0.1 < \tau < 6.7 \text{ Gyr},$$  \hspace{1cm} (5)

Figure 17. Bolometric luminosity evolution in the stellar models used in this work to calculate the history of low-mass star UV illumination.

where $\tau$ is in units of Gyr. We take the current age of the Sun to be 4.6 Gyr, and this flux is evaluated at a distance of 1 au. Although the EUV bands from Ribas et al. (2005) and France et al. (2018) are different, this conversion allows a representative evolutionary history for the Sun-like N V emissions, which we can compare with the activity–age evolution determined for M dwarfs in Section 5.1. Because Equation (5) is only applicable to a particular age interval, to extrapolate to younger ages, we consider the UV emissions at $\tau=0.1$ Gyr to correspond to a saturated level relative to bolometric that is constant for $\tau<0.1$ Gyr, log $L_{\text{N}\text{V}}/L_{\text{bol}} = -5.75$, set by the model bolometric luminosity at $\tau=0.1$ Gyr. We then let the bolometric luminosity change according to the nonmagnetic Dartmouth stellar models for $\tau<0.1$ Gyr (e.g., Dotter et al. 2008).

We show our results in Figure 18 as the accumulated N V emission experienced by a planet at a fixed distance of 1 au from its host, for the three planet host cases, 0.25 $M_\odot$, 0.60 $M_\odot$, and 1.0 $M_\odot$, starting at 1 Myr, the lower limit of the evolutionary models. The absolute N V illumination is typically higher around the higher-mass objects than around the lower-mass stars. The shaded bands in Figure 18 propagate the uncertainty in the median evolution (as in Figure 16) through the integral of Equation (4). We do not include the intrinsic scatter, because we focus here on the cumulative average history from the rotation–activity analysis. Our treatment, however, excludes uncertainty from unknown systematics with
the bolometric luminosity evolution, although at least with regards to the role of magnetism, its contribution may be minor (see Figure 17). Ribas et al. (2005) did not report uncertainties for their EUV evolution in Sun-like stars, and we thus do not include it either.

In Figure 19, we also show the ratios ($E_{0.60}/E_\odot$, $E_{0.25}/E_\odot$, and $E_{0.25}/E_{0.60}$) of the accumulated UV energies, propagating the uncertainty in the M-dwarf median rotational evolution. The left-side axes give the result for planets at equal distances around each star, and the right-side axes indicate the same ratio but for the respective habitable zones. This further assumes planets at that distance have remained there throughout history. The curves of the right axis are thus a constant multiple of those of the left axis, as in

$$\frac{E_t}{E_\odot} \bigg|_{\text{HZ}} = \int_0^t \frac{R_a L_{bol,a} \, d\tau}{\int_0^t \frac{R_b L_{bol,b} \, d\tau}{d_{HZ,b}^2}} \times \frac{d_{HZ,b}^2}{d_{HZ,a}^2},$$

where the habitable zone distances are determined by the 5 Gyr bolometric instellations. The right-side axes in Figure 19 thus indicate the relative accumulated UV energies for planets in the respective field-age habitable zones of each star.

In Figure 19, we illustrate that, in the low-mass star regime, at a constant distance, exoplanets orbiting higher-mass objects experience a greater absolute accumulation of UV energy. However, within the respective habitable zones around each host, the planets orbiting the lower-mass star intercept much more UV energy. For example, relative to the Earth around the Sun, the same planet in the habitable zone around the 0.25 $M_\odot$ star will accumulate $\sim$20 times more UV energy by the time it has reached field age, which is $\sim$2 times more than the same planet in the habitable zone around the 0.60 $M_\odot$ star. Within the known uncertainty of the median rotational evolution, these figures can vary by factors of a couple. The curves of Figure 19 reflect at early times the differential bolometric luminosity evolution modulated by activity–age evolution at late times, with modulations of the evolution dictated by the age at which each star begins its power-law decay of UV activity. The bottom panel of Figure 19 also shows the results using both magnetic (dashed line) and nonmagnetic (solid line) models to illustrate that similarity of the luminosity evolution, as well as the robustness of our results to this potential systematic effect.

These results were derived specifically using N V emissions; however, the line is broadly representative of the entire FUV band, given the strong correlations between emission lines (Section 3.4). Thus, although the absolute energy levels
determined from Equation (4) and shown in Figure 18 will vary between different choices of UV features, the ratios of Figure 19 are broadly representative of total FUV emissions. Moreover, to the extent that the N V emission is directly proportional to EUV emissions (France et al. 2018), the ratios of Figure 19 translate exactly to the relative exposure of planets to EUV emissions around each stellar host. This is a key result, given the importance of EUV fluxes for exoplanetary atmospheric heating and escape.

In Figure 20, we further show the importance of different epochs in the total accumulated UV exposure for exoplanetary systems. Relative to the cumulative quiescent UV energy experienced at an age of 5 Gyr, planets around low-mass hosts reach total energetic exposures exceeding ~50% by ages of 800, 600, and 250 Myr, respectively, for hosts of mass 0.25, 0.60, and 1.0 M . These results quantify the importance of the first Gyr of stellar lifetimes in their total energetic input to exoplanetary systems. These early ages clearly need to be taken into account when considering the evolutionary histories of planetary systems and their responses to high-energy emissions.

6. Conclusions

The UV data of the FUMES sample presented in this paper, combined with the literature data, have allowed us to examine how the far-ultraviolet spectroscopic emissions of low-mass stars change with angular momentum evolution over time. At fast rotation rates (Rossby number Ro ≤ 0.2), corresponding to young stellar ages (≤ 1) Gyr, the FUV lines exhibit saturated emissions at levels of 10⁻³⁻⁵⁻³ to relative to the stellar bolometric luminosity, depending on the specific line, with Lyα being the strongest feature. As the stars spin down with age, these emission levels drop by ~2 orders of magnitude for typical field ages. However, this decline appears to be weakest in Lyα, which will change the spectroscopic balance of energy output (i.e., FUV/NUV ratio) between young and old M dwarfs. This evolutionary behavior is evident throughout the M-dwarf sample for both early- and mid- to late-M dwarfs. Because these stars show similar FUV luminosities relative to bolometric, the early-M dwarfs are more UV luminous in absolute terms, but with potentially different spin-down behaviors; the cooler stars may emit at the saturation levels for a greater duration of their early lifetimes. This evolutionary behavior may have several implications across stellar astrophysics and exoplanetary science.

6.1. Stellar Atmospheres and Dynamos

The FUV emission lines directly probe the transition region of the stellar coronal atmosphere. Our spectroscopic data showed how the different features change with rotation, directly implying how the atmospheric structure changes across time, between active and inactive low-mass stars. These data can thus be used to directly assess those changes through stellar chromospheric and coronal models (e.g., Fontenla et al. 2016; Peacock et al. 2019). The comparison of the rotation–activity relationships across Ho, the FUV, and X-rays, however, suggests more significant changes in the corona with spin-down relative to the changes in the deeper layers of the atmosphere. These differences must be a direct consequence of how the nonthermal heating processes change with rotation rate. Models of the magnetic heating process itself in M dwarfs must be able to account for these evolutionary effects as well as their significance at different layers of the atmosphere.

This aspect of nonthermal chromospheric/coronal heating is an important consideration in making dynamo inferences, because the observed rotation–activity relationships in different wave bands, often used for this endeavor, are mediated by the magnetic heating and are not directly defined by the dynamo processes. The multiwavelength rotation–activity relationships need to be reconciled with more homogeneous methodologies, including the possibly different behaviors in different upper atmospheric layers, in order to provide definitive conclusions with respect to dynamo theory. Crucially, while our analysis shows that a Rossby scaling works well for normalizing the rotation–activity relationships in both partly and fully convective M dwarfs, the empirical scaling may be masking real differences in these populations. This effect is potentially evident in alternative scalings; however, larger samples are required to examine these differences in the UV, to compare with other wave bands (e.g., Magaudda et al. 2020).

6.2. Exoplanets

The stellar high-energy spectrum largely defines the prevalent photochemistry and mass-loss history of exoplanetary systems. While these effects have often been investigated in the context of individual nearby planets around low-mass stars, the present-day observations of the planetary atmosphere have been shaped by the cumulative history of these stellar emissions. Our spectroscopic FUV data provide the rotational evolution for M-dwarfs directly, which can be transformed using rotation–age gyrochronology relationships. Although the latter remain uncertain for M dwarfs, their improvement will greatly improve our assessments of this evolutionary history. Employing literature scaling relations using FUV emission features then enables estimates across the high-energy spectrum, including the EUV (e.g., France et al. 2016, 2018). To understand exoplanetary atmospheres, this stellar emission history needs to be taken into account.

Of particular importance is the likely difference between early- and mid- to late-M dwarfs, with regard to how long they persist in exhibiting near saturation level activity. By old field
ages, planets in similar orbits around these two different kinds of hosts will likely have experienced different histories in high-energy radiative environments (e.g., Luger & Barnes 2015). Moreover, changes in the relative significance of FUV or NUV emissions over time will influence the prevalent exoplanetary atmospheric molecules that are observable today. Our results enable a way to account for these effects across different emission features and wave bands when considering new exoplanetary systems.

Using our rotation–activity correlation fits (Section 4), assuming no residual mass dependence, we can predict the most prominent FUV emission features in quiescence from a known rotation period and mass to generally within 0.3 dex of intrinsic scatter. This scatter pertains to the sample population and is likely a consequence of the combined effects of activity cycles, rotation variations in visible active regions, metallicity differences, and/or the stochastic nature of magnetic heating. As an example, we imagine a 0.4 \( M_\odot \) star with a 60 day rotation period, with 3% uncertainty on the mass and 5% in the rotation period. Accounting for scatter in the Rossby number calibration and our best-fit parameters, our rotation–activity correlations would predict a mean value of \( \log(L_{\text{CIV}}/L_{\text{bol}}) = -6.21 \pm 0.16 \). With improved rotation–age relations, our data will enable a more comprehensive assessment of the high-energy radiative input to exoplanetary systems across time.

7. Summary

In this paper, we have examined the far-ultraviolet emission of M-dwarf stars, as probes of the stellar upper atmosphere and nonthermal magnetic heating, their rotational evolution, and possible implications for planetary systems orbiting these kinds of hosts. Additional FUMES papers will discuss the \( \text{Ly}_\alpha \) reconstructions (Youngblood et al. 2021) as well as time variability in the UV/optical emissions (Duvvuri et al. 2021). For this work, our primary findings are summarized below.

1. We reported emission line–emission line correlations across \( \sim 3 \) orders of magnitude for the FUV features with respect to C IV emissions, revealing \( \sim 0.1–0.2 \) dex of intrinsic scatter between FUV features defining the extent to which such features can be used to predict one another across the M-dwarf population; see Section 3.4.
2. We provided rotation–activity correlations as a function of Rossby number across eight UV features, including \( \text{Ly}_\alpha \), with typical power-law slopes of \(-2\) and critical Rossby numbers of 0.2; see Section 4.
3. The decay of \( \text{Ly}_\alpha \) emission with rotation is likely weaker than it is for other FUV features, implying evolutionary changes in the relative balance of UV spectroscopic emissions; see Section 4.2.
4. A possible trend in the rotation–activity correlations as a function of atmospheric layer points to the importance of disentangling magnetic heating effects through the stellar atmosphere when investigating the dynamo dependence on rotation rate; see Section 4.3.
5. We demonstrated systematic effects in the resulting fit parameters for rotation–activity correlations (power-law slope, critical Rossby number) when utilizing different empirical calibrations for the convective turnover time as a function of mass; see Appendix A.2.

6. Mid- to late-M dwarfs may exhibit saturation-level FUV activity for a longer duration of their early lifetimes relative to early-M dwarfs, with correspondingly distinct histories of high-energy emission impacting exoplanetary systems around these hosts; see Section 5.
7. Planets in the habitable zones around mid- to late-M dwarfs, at field ages, will have accumulated \( \sim 2\times \) more EUV exposure than planets around early-M dwarfs, and \( 20\times \) more exposure than planets in the habitable zones around Sun-like stars; see Section 5.2.
8. For planets orbiting low-mass stars, the majority of energetic UV exposure accumulated by the age of 5 Gyr was experienced during the saturated phase of activity evolution, lasting \( \sim 1 \) Gyr; see Section 5.2.

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Based on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium.

Facilities: HST (STIS), Blanco (ARCoIRIS), APO (TSPEC).

Appendix

A.1. Concerning the Use of Surface Fluxes

In Section 3.4, we correlated FUV line flux measurements, illustrating tight relationships between different emission features probing distinct temperatures of the transition region. In the literature, these kinds of correlations have been expressed similarly, but instead of luminosity, they have been expressed using the surface flux, normalizing the luminosities by the stellar surface area (e.g., Wood et al. 2005; Youngblood et al. 2017). While this attempts to normalize the emissions accounting for the area of the emitting region to enable comparisons across different kinds of stars, the inclusion of the radii introduces additional uncertainty and increases the error correlations, as the radius uncertainty will dominate the error budget relative to the parallax and flux measurements. In Figure 21, we illustrate this effect using the same data for C IV and Si IV that comprise the upper right panel of Figure 5, but transforming the emission measurements to surface flux with

\[ \text{This effect was less significant in the past, when parallaxes were not known as precisely (pre-Gaia).} \]
the radius determinations from Table 2. The representative 2σ error ellipses now are all highly inclined, revealing the strong correlations between the uncertainties in each quantity.

The power-law slope estimated in such line–line correlations using the surface flux should be identical to the luminosity approach used in this work; however, the uncertainties on such estimates do not accurately reflect the nature of the underlying data if they do not account for this correlated error, and they are less precisely constrained when accounting for the actual radii uncertainty in the analysis. This additional uncertainty may obscure intrinsic scatter in the analyzed correlations. We therefore recommend luminosity as a currently more robust choice when defining predictive relations between stellar emission features. However, whenever surface fluxes are necessary, a careful accounting of possible correlations should be included.

### A.2. Systematics with the Convective Turnover Time

In Section 4, we analyzed the rotation–activity relation of M-dwarfs in FUV emission lines with the FUMES and literature samples. We used the empirical calibration of Wright et al. (2018) to estimate the convective turnover time from the stellar mass in computing the Rossby number, $\text{Ro} = P/\tau_c$, for each star. This empirical calibration is based on minimizing the scatter in the X-ray rotation–activity correlation of low-mass stars. Wright et al. (2011) details the typical procedures used in developing this kind of empirical calibration. Since the Ro is generally closely related to the internal dynamo action (although see Reiners et al. 2014), the use of this kind of calibration enables a dynamo comparison among stars with convective interiors, from F- to M-type stars. However, changes in the kind of magnetic dynamo that generates field in fully convective stars, for example $\alpha$–$\Omega$ instead of $\alpha$–$\Omega$ (e.g., Browning 2008), suggest that there is no physical reason a single such calibration should work across that full range. Moreover, with relatively deeper convective zones, a single representative value for the timescale of convective motions is likely an increasingly poor approximation with decreasing stellar mass. Accordingly, although the empirical calibration reduces the X-ray rotation–activity scatter, it may not be representative of the dynamo behavior in the fully convective regime.

Nevertheless, using these relations provides a means to compare to literature results and test how the X-ray-calibrated relation applies to the activity at other wavelengths, as we have done in Section 4. As detailed in this appendix, we further investigated how those results are impacted by the choice of empirical calibration for the convective turnover time as a function of stellar mass. In Figure 22, we plot three such literature calibrations from Wright et al. (2011), Núñez et al. (2015), and Wright et al. (2018), including the scatter about those relationships, as reported in those works or obtained via private communication (0.064 dex, Núñez, A.). The Núñez et al. (2015) calibration uses the same data as Wright et al. (2011), but assumes the canonical value for the best-fit slope ($−2$) instead of the best-fit value from Wright et al. (2011), and the Wright et al. (2018) calibration, which sits in between the other two, updates the Wright et al. (2011) result with more fully convective stars and a slightly different functional form.

We refit the rotation–activity data presented in Section 4, using the same methods—but also using the two additional literature calibrations in order to determine their impact on the best-fit parameters. These results are shown in Table 9 for the critical Rossby number, $\text{Ro}_c$, and in Table 10 for the slope of the unsaturated regime, $\eta$. The effect of the different calibrations is most readily illustrated by comparing the results using Wright et al. (2011) versus Núñez et al. (2015), as they have a greater separation in $\tau_c$–$M$ space (see Figure 22). The Núñez et al. (2015) calibration gives higher convective turnover times at a given mass than that of Wright et al. (2011). Consequently, the best-fit $\text{Ro}_c$ is systematically smaller using Núñez et al. (2015) than it is when using the Wright et al. (2011) calibration—higher $\tau_c$ corresponds to smaller $\text{Ro}_c$. Between the two calibrations as applied to our data, this yielded a systematic offset of $\sim0.04–0.05$ in $\text{Ro}_c$; see Table 9.

This effect on the best-fit critical Rossby number is relatively intuitive, given the direct impact on the convective turnover time between calibration choices. However, we also observe a systematic difference in the best-fit slope from the rotation–activity analysis when changing between empirical
increase the magnitude of this systematic effect on the best-
number of fully convective stars in the sample would likely
generally not the case. Thus, depending on the sample of stars,
the mass-dependent convective turnover time.

Figure 23. Changing the assumed calibration for convective turnover time as a
function of stellar mass when fitting the canonical rotation–activity relation-
ships systematically affects the best-fit parameters for the unsaturated slope, \( \eta \),
and critical Rossby number, \( R_\text{c} \). Representative error ellipses shown here for
four of the FUV line rotation–activity fits collectively shift, yellow (Núñez
et al. 2015) relative to blue (Wright et al. 2011), when using distinct
calibrations; see Appendix A.2.

Note. Bold values indicate results used in analyses of Section 4.4.
* Reported parameters correspond to the median of the marginalized posterior
distribution, with uncertainties indicating the central 68% confidence interval.
The reference for each column indicates the source used for the calibration of
the mass-dependent convective turnover time.

| Line | Wright et al. (2011) | Núñez et al. (2015) | Wright et al. (2018) |
|------|---------------------|---------------------|---------------------|
| Lyα | 0.25±0.12           | 0.19±0.10           | 0.21±0.11           |
| Mg II | 0.23±0.06          | 0.19±0.08           | 0.20±0.08           |
| C II | 0.28±0.14           | 0.20±0.09           | 0.24±0.12           |
| Si III | 0.23±0.08         | 0.18±0.06           | 0.20±0.07           |
| He II | 0.22±0.06           | 0.16±0.04           | 0.19±0.05           |
| Si IV | 0.28±0.08           | 0.22±0.06           | 0.24±0.07           |
| C IV | 0.22±0.08           | 0.17±0.06           | 0.18±0.06           |
| N V | 0.22±0.09           | 0.18±0.06           | 0.19±0.07           |

Note. Bold values indicate results used in analyses of Section 4.
* Reported parameters correspond to the median of the marginalized posterior
distribution, with uncertainties indicating the central 68% confidence interval.
The reference for each column indicates the source used for the calibration of
the mass-dependent convective turnover time.

| Line | Wright et al. (2011) | Núñez et al. (2015) | Wright et al. (2018) |
|------|---------------------|---------------------|---------------------|
| Lyα | –1.21±0.34          | –1.25±0.36          | –1.26±0.38          |
| Mg II | –1.72±0.37          | –1.86±0.44          | –1.86±0.41          |
| C II | –2.25±0.32          | –2.25±0.37          | –2.38±0.64          |
| Si III | –1.94±0.39        | –2.10±0.41          | –2.08±0.41          |
| He II | –2.11±0.37          | –2.15±0.30          | –2.19±0.30          |
| Si IV | –2.21±0.40          | –2.31±0.42          | –2.32±0.42          |
| C IV | –1.92±0.37          | –2.04±0.37          | –2.02±0.39          |
| N V | –1.76±0.38           | –1.88±0.37           | –1.84±0.37          |

Núñez et al. (2015), as that is where those functions largely
diverge. It is therefore difficult to estimate the extent of this
systematic effect on the slopes without doing the entirety of the
analysis with multiple calibrations for \( \tau_c \) for each sample of
stars. This makes it somewhat more difficult to draw
comparisons across the literature, as methods have been
updated and evolved over time, with different stellar samples.
Future comparisons across wave bands and samples will
greatly benefit from homogeneous analysis methodologies.
The framework presented in this paper for the rotation–activity
work (Section 4) accounts for known uncertainties across all
available data, as well as possible correlations, and it includes a
measure of the intrinsic scatter within the regression fit. The
presence of these systematics effects, especially when using a
quantity as uncertain as the convective turnover timescale, also
supports the argument in favor of finding simpler descriptions
that capture the relevant physics for characterizing the
dependence of activity on stellar physical and rotational
properties, as discussed in Reiners et al. (2014). We tested
some of those methods in Section 4.4.

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