Ly α Observations of High Radial Velocity Low-mass Stars Ross 1044 and Ross 825

Adam C. Schneider¹ , Evgenya L. Shkolnik¹ , Travis S. Barman² , and R. Parke Loyd¹

¹ School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85282, USA; aschneid10@gmail.com

² Lunar & Planetary Laboratory, University of Arizona, 1629 E. University Blvd, Tucson, AZ 85721, USA

Received 2019 September 6; revised 2019 September 23; accepted 2019 September 26; published 2019 November 14

Abstract

The discovery of habitable zone (HZ) planets around low-mass stars has highlighted the need for a comprehensive understanding of the radiation environments in which such planets reside. Of particular importance is knowledge of the far-ultraviolet (FUV) radiation, as low-mass stars are typically much more active than solar-type stars and the proximity of their HZs can be one-tenth the distance. The vast majority of the flux emitted by low-mass stars at FUV wavelengths occurs in the Ly α line at 1216 Å. However, measuring a low-mass star's Ly α emission directly is almost always impossible because of the contaminating effects of interstellar hydrogen and geocoronal airglow. We observed Ross 825 (K3) and Ross 1044 (M0), two stars with exceptional radial velocities, with the Space Telescope Imaging Spectrograph on board the *Hubble Space Telescope*. Their radial velocities resulted in significant line shifts, allowing for a more complete view of their Ly α line profiles. We provide an updated relation between effective temperature and Ly α flux using *Gaia* DR2 astrometry as well as updated, model-independent relationships between Ly α flux and UV flux measurements from the *Galaxy Evolution Explorer* (GALEX) for low-mass stars. These new relations, in combination with GALEX's considerable spatial coverage, provide substantial predictive power for the Ly α environments for thousands of nearby, low-mass stars.

Unified Astronomy Thesaurus concepts: Low mass stars (2050)

Supporting material: data behind figure

1. Introduction

Both K- and M-type stars have distinct advantages for studying exoplanets. M dwarfs are the most abundant stars in the Galaxy (Bochanski et al. 2010), have large planet occurrence rates (Dressing & Charbonneau 2015; Hardegree-Ullman et al. 2019; Tuomi et al. 2019), have numerous observational advantages for exoplanet characterization, and have therefore emerged as targets for current and future exoplanet investigations. K dwarfs, while not as numerous as M dwarfs, also have substantial planet occurrence rates (Mulders et al. 2015), and the reduced X-ray and UV radiation incident on habitable zone (HZ) planet atmospheres around K dwarfs has led some to suggest that K dwarfs might be the most promising targets for the detection of biology outside of our solar system (Heller & Armstrong 2014; Cuntz & Guinan 2016; Arney 2019; Richey-Yowell et al. 2019). For these reasons, understanding the properties of both K and M dwarfs is an essential component of current and upcoming planet-hunting missions such as the *Transiting Exoplanet Survey Satellite* (TESS) and *PLANetary Transits and Oscillations of stars* (PLATO; Rauer et al. 2014; Ricker et al. 2015).

The UV radiation emitted by low-mass stars can chemically modify, ionize, and even erode a planetary atmosphere over time, drastically affecting their habitability (Kasting et al. 1993; Lichtenegger et al. 2010; Segura et al. 2010; Hu et al. 2012; Luger & Barnes 2015). Furthermore, several studies have shown that incident UV flux could lead to the formation of abiotic oxygen and ozone, resulting in potential false-positive biosignatures (Domagal-Goldman et al. 2014; Tian et al. 2014; Harman et al. 2015). The most prominent far-ultraviolet (FUV) emission line, Ly α (λ 1215.67 Å), comprises $\sim$ 37%–75% of the total 1150–3100 Å flux from most late-type stars (France et al. 2013). Because Ly α can affect the photodissociation of important molecules such as H₂O and CH₄, any photochemical

models assessing potential biosignatures or atmospheric abundances will require accurate Ly α host star flux estimates (e.g., Rugheimer et al. 2015).

In almost all cases, Ly α cannot be directly observed because of (1) attenuation of photons by optically thick hydrogen absorption located in the intervening interstellar medium (ISM) and (2) contamination from Earth's own Ly α geocoronal airglow. In fact, there exists only one complete Ly α spectrum in the *Hubble Space Telescope* (HST) archive, that of Kapteyn's star (an M1 subdwarf; Guinan et al. 2016). With a radial velocity (RV) of 245 km s^{−1}, its stellar Ly α emission feature is shifted out of the geocoronal line core and ISM absorption.

For all other stars, Ly α emission may only be estimated. Wood et al. (2005) reconstructed Ly α fluxes by determining interstellar hydrogen column densities and velocities inferred from deuterium and metal lines. Alternatively, reconstructions have been performed by fitting 1 or 2 Gaussians to what remains of the wings of the Ly α profile (France et al. 2012; Youngblood et al. 2016, 2017). Such reconstructions have been used extensively to produce correlations between Ly α fluxes and other spectral emission lines (Linsky et al. 2013) and broadband UV photometry (Shkolnik et al. 2014) from the *Galaxy Evolution Explorer* (GALEX). These correlations have been used to evaluate the capabilities of different spectral types to develop and sustain life (e.g., Cuntz & Guinan 2016).

The lack of observational Ly α constraints on low-mass stars has limited progress in predicting the environments that surround them. In an effort to further inform models of low-mass stellar UV flux levels, we have extended the observational sample of stars for which the shape and majority of Ly α flux can be measured beyond just Kapteyn's star. We identified two low-mass targets, Ross 825 (K3) and Ross 1044 (M2).

Table 1
Target Sample

Property	Ross 825	References	Ross 1044	References
2MASS Name	21111696+3331272	1	15032457+0346574	1
Spectral Type	K3	2	M0	3
π (mas)	10.17 ± 0.08	4	26.9 ± 8.4	5
μ_α (mas yr ⁻¹)	502.63 ± 0.17	4	-899.1 ± 4.7	5
μ_δ (mas yr ⁻¹)	159.31 ± 0.29	4	695.3 ± 4.6	5
RV (km s ⁻¹)	-340.17 ± 0.67	4	-169.55 ± 1.80	4
Age (Gyr)	>10	3	>10	3

References. (1) 2MASS, Skrutskie et al. (2006); (2) Bidelman (1985); (3) This work; (4) Gaia Collaboration et al. (2016, 2018); (5) Finch & Zacharias (2016).

2. Target Sample

Targets for this program were chosen based on their spectral types (later than K0), distances (within 100 pc), and large absolute RVs. We chose a radial velocity threshold of 150 km s^{-1} , which results in a $\approx 0.6 \text{ \AA}$ wavelength shift of the $\text{Ly}\alpha$ emission line. Such stars are rare because the vast majority of low-mass stars in the solar neighborhood have absolute radial velocities less than 50 km s^{-1} . Shkolnik et al. (2012) found an average RV of 1.6 km s^{-1} with a standard deviation of 23.9 km s^{-1} for a sample of 159 M dwarfs within 25 pc.

We identified two targets, Ross 825 and Ross 1044, that satisfied these criteria and were bright enough to acquire a suitable signal-to-noise ratio (S/N) in a reasonable amount of *HST* time. The properties of these two stars are summarized below.

2.1. Ross 825

Ross 825 was first identified as a high proper motion star by Ross (1929), who estimated a total proper motion of $0''.48 \text{ yr}^{-1}$. Bidelman (1985) compiled spectral classifications determined by G. P. Kuiper and published a spectral type of K3 for Ross 825. Ross 825 was also noted as a close visual double in that work. The RV of Ross 825 was first measured in Carney & Latham (1987), who determined a value of $-340.68 \text{ km s}^{-1}$.

Gaia observations (Gaia Collaboration et al. 2016, 2018) of Ross 825 confirmed the binary nature of this source (separation $\approx 1''.6$) and its RV ($-340.16 \pm 0.67 \text{ km s}^{-1}$). It is also resolved as a binary in the Space Telescope Imaging Spectrograph (STIS) acquisition images acquired through this investigation. Stassun et al. (2018) provided an effective temperature estimate (T_{eff}) of $4680 \pm 177 \text{ K}$, which corresponds to a spectral type between K3 and K4 (Pecaut & Mamajek 2013), consistent with its measured spectral type. Schuster et al. (2006) provided *ubvy*- $\text{H}\beta$ photometry of Ross 825 and determined a photometric metallicity of $[\text{Fe}/\text{H}] = -1.28$ based on empirical relations. An $[\text{Fe}/\text{H}]$ value of -1.28 implies an age $>10 \text{ Gyr}$ according to the models of Dotter et al. (2017), which is supported by its large absolute radial velocity. Relevant properties of Ross 825 are summarized in Table 1.

2.2. Ross 1044

Ross (1939) identified Ross 1044 as a high proper motion star with a total proper motion of $1''.27 \text{ yr}^{-1}$. A spectral type of K7 was first published for this star in Bidelman (1985). Newton et al. (2014) determined a near-infrared spectral type of M2 for Ross 1044. We determine a spectral type of M0 by comparing

Table 2
HST/STIS Observations

Object	Obs. Dates UTC	Exposure Time (s)
Ross 825	2018 Jul 30, 2018 Aug 3	17079
Ross 1044	2018 Nov 26, 2018 Nov 30	15186

the publicly available optical spectrum from the Palomar/MSU (Michigan State University) survey (Reid et al. 1995) to Sloan Digital Sky Survey (SDSS) standards (Bochanski et al. 2010). Ross 1044 was found to have a large absolute RV in the Palomar/MSU nearby star spectroscopic survey (-159.1 km s^{-1} ; Reid et al. 1995). This RV was confirmed in Newton et al. (2014) ($-174 \pm 5 \text{ km s}^{-1}$) and *Gaia* DR2 ($-169.55 \pm 1.80 \text{ km s}^{-1}$). Ross 1044 was also found to have a low metallicity ($[\text{Fe}/\text{H}] = -1.01 \pm 0.21$; Newton et al. 2014), which is consistent with an age $>10 \text{ Gyr}$ (Dotter et al. 2017). This star also showed no clear signature of $\text{H}\alpha$ either in emission or absorption in the optical spectrum from the Palomar/MSU survey (Reid et al. 1995). Note that while Ross 1044 has a measured RV in *Gaia* DR2, there is no parallax available. This is likely because Ross 1044 has a `visibility_periods_used` value of 5 in the *Gaia* DR2 catalog, which does not satisfy the criterion needed for a five-parameter solution in Equation (11) of Lindegren et al. (2018). Two parallax measurements exist in the literature: $47.0 \pm 4.1 \text{ mas}$ (van Altena et al. 1995) and $26.9 \pm 8.4 \text{ mas}$ (Finch & Zacharias 2016). The “quality of interagreement” is listed as “Poor” in van Altena et al. (1995), and we therefore adopt the Finch & Zacharias (2016) parallax for this work. Relevant properties of Ross 1044 are summarized in Table 1.

3. Observations

We observed Ross 825 and Ross 1044 during *HST* Cycle 25 with STIS on board *HST* (PID #15286). For these observations, STIS is preferred over the Cosmic Origins Spectrograph (COS) because COS is a slitless spectrograph, which results in heavy contamination in the $\text{Ly}\alpha$ region from geocoronal emission. We employed the G140M grating ($R \sim 11400$) with a $52'' \times 0''.1$ slit. For each observation, we set the central wavelength to $1222 \text{ \AA}$. Observing dates and total exposure times are provided in Table 2.

For several of the visits for each object, the *HST calstis* pipeline failed to locate the correct location of the star. For both stars, we determined trace positions manually and reran the *calstis* pipeline for every visit. For Ross 825, one visit was especially noisy and a trace position could not be determined. These data are not included in the final spectrum. Final spectra

Figure 1. *HST*/STIS spectra (black lines) for Ross 1044 (left) and Ross 825 (right). The best-fitting model is shown in blue, with the resulting intrinsic Ly α flux shown in red. The ISM transmittance curve is shown as a dotted line.

(The data used to create this figure are available.)

were produced by coadding the spectra for each visit together for each star and are shown in Figure 1. While the binary nature of Ross 825 was seen in the STIS acquisition images, the Ly α spectrum comes solely from the primary component of this system. All subsequent analysis of Ross 825 corresponds exclusively to the primary object of this pair.

4. Analysis

4.1. Ly α Line Profiles

For both Ross 825 and Ross 1044, the majority of their Ly α emission is directly measured with our STIS observations. However, neither target is immune to intervening ISM absorption. For this reason, ISM modeling is necessary to retrieve the intrinsic Ly α flux for both stars. Following Bourrier et al. (2015), we model the ISM using Voigt profiles for both atomic hydrogen and deuterium. We fix the D I/H I ratio to 1.5×10^{-5} (Hébrard & Moos 2003; Linsky et al. 2006). We fix the RV of the Ly α emission to the stellar RV measurements given in Table 1. Free parameters then include the intrinsic Ly α flux, the column density of hydrogen, and the RV of the intervening ISM. While there may be multiple ISM components along the line of sight to each star, we model them as a single component.

Whether or not intrinsic Ly α line profiles contain a self-reversal, making them single- or double-peaked, is a large source of uncertainty for Ly α reconstructions, leading to flux differences as large as 30% (Youngblood et al. 2016). For strong lines, such as Ly α , the emission in the wings and the core of the line can form in different atmospheric layers, leading to self-reversals in the core (Peacock et al. 2019). While the Sun shows a self-reversal in its Ly α core, Youngblood et al. (2016) argue that M dwarf Ly α profiles should be single-peaked because M dwarf Mg II profiles show signs of self-absorption. However, we note that the presence of reversals in observed Mg II line cores of M dwarfs is also a

consequence of spectral resolution. Fontenla et al. (2016) presented a STIS/E230H spectrum of the M2 star GJ 832, which shows clear signs of reversals in its Mg II line cores. These reversals are not seen in the MUSCLES NUV spectra (see Figure 5 of France et al. 2016), which were taken with the COS/G230L setting, which has ~ 1 order of magnitude less spectral resolution than STIS/E230H.

Our STIS spectra have resolutions similar to COS/G230L. All models are convolved with the STIS line-spread function to compare to observations. For Ross 1044, the Ly α line shows a clear Gaussian shape, and the peak of the Ly α emission occurs at the same RV as the stellar RV measurement. Ross 825, on the other hand, has Ly α emission peaking approximately 60 km s^{-1} away from the measured stellar RV, suggestive of a double-peaked profile. We therefore model our M dwarf target (Ross 1044) without a self-reversal and explore models with and without self-reversals for our K dwarf target (Ross 825). Note that a similar RV offset between peak Ly α emission and the stellar RV is seen for Kepler-444 (spectral type = K1), which has an RV of -121.4 km s^{-1} (Dupuy et al. 2016). Bourrier et al. (2017a) found that the Ly α emission for *Kepler*-444 is best fit by a double-peaked profile.

For Ross 1044 we use a model consisting of two Gaussians, one strong and narrow and the other weaker and broad, following Youngblood et al. (2016). We also fit the Ross 825 data with two Gaussians, though the second Gaussian in this case is subtracted from the first to account for the presence of a self-reversal in the line core. We find posterior distributions for each model parameter using the *emcee* package (Foreman-Mackey et al. 2013). For each fit, we run 1000 walkers with 1000 steps, treating the first 300 steps as the burn in sample. For both objects, we also performed a fit with a single Gaussian, and the two-Gaussian solution is preferred in both cases according to the Bayesian information criterion (BIC). For Ross 825, we also attempted a three-Gaussian fit—broad and narrow profiles as with Ross 1044 and a third component

Figure 2. Left: STIS Ly α spectra of Ross 1044 for all six visits compared to the final coadded spectrum. Right: Ly α flux variability of Ross 1044. All points are normalized to the flux of the final coadded spectrum.

Table 3
emcee Best-fit Model Parameters

Model Parameter	Ross 1044		Ross 825	
	Prior	Value	Prior	Value
Amplitude 1 (10^{-14} erg s $^{-1}$ cm $^{-2}$ Å $^{-1}$)	$\mathcal{U}(0,10)$	$3.75^{+0.34}_{-1.46}$	$\mathcal{U}(0,10)$	$1.86^{+1.82}_{-0.96}$
Sigma 1 (km s $^{-1}$)	$\mathcal{U}(0,5)$	0.24 ± 0.01	$\mathcal{U}(0,10)$	$0.27^{+0.12}_{-0.02}$
Amplitude 2 ^a (10^{-14} erg s $^{-1}$ cm $^{-2}$ Å $^{-1}$)	$\mathcal{U}(0,5)$	$1.55^{+1.82}_{-0.96}$	$\mathcal{U}(0,5)$	$0.31^{+0.61}_{-0.20}$
Sigma 2 ^a (km s $^{-1}$)	$\mathcal{U}(0,25)$	$0.35^{+1.57}_{-0.12}$	$\mathcal{U}(0,5)$	$0.24^{+0.17}_{-0.03}$
RV _{ISM} (km s $^{-1}$)	$\mathcal{U}(-50,50)$	$16.32^{+5.18}_{-3.93}$	$\mathcal{U}(-50,50)$	$-13.39^{+30.63}_{-24.77}$
10^{18} cm $^{-2}$ /d ^b (pc)	$\mathcal{U}(4,50)$	$13.58^{+3.28}_{-2.46}$	$\mathcal{U}(4,50)$	$5.95^{+2.72}_{-1.44}$

Notes.

^a The Gaussian described by Amplitude 2 and Sigma 2 was added to the first Gaussian in the case of Ross 1044, and subtracted in the case of Ross 825.

^b Range of H I column densities taken from Redfield & Linsky (2008).

subtracted out. Again, the BIC prefers the two-Gaussian model compared to the three-Gaussian case. Our model fits imply that our STIS observed spectra recovered $\sim 74\%$ and $\sim 63\%$ of the total intrinsic Ly α flux for Ross 1044 and Ross 825, respectively. These percentages are significantly higher than that typically seen for field M dwarfs, which is usually $\lesssim 30\%$ (Youngblood et al. 2017). The best-fitting profiles are shown in Figure 1 with the best-fit parameters given in Table 3 and the resulting Ly α fluxes are provided in Table 4.

5. Discussion

5.1. Ly α Variability of Ross 1044

Ross 1044 has sufficient S/N in each of the six visits to investigate for variability in the strength of the Ly α line. In Figure 2, we plot the the individual spectra from each visit, as well as our combined final spectrum. While the general shape and flux are similar for each of the six visits, the total flux for the first three visits is less than that from the last three visits. We quantify this by summing up the total flux in each visit, then normalizing to the total flux from the final combined spectrum, with uncertainties calculated in a Monte Carlo fashion. We find that the total flux varied by $\sim 20\%$ between the smallest and largest flux values measured. Note that there

exists an STIS “breathing” effect, which can cause variability within *HST* orbits (Brown et al. 2001; Sing et al. 2008). This effect should be mitigated by the use of spectra averaged over each visit. The Ly α variability of Ross 1044 is consistent with that seen in the Ly α line of GJ 1132, where a variability up to 22% is seen (Waalkes et al. 2019), and Kepler-444, where variability of 20%–40% is seen between visits (Bourrier et al. 2017a). This is also consistent with the variability seen in other UV spectral lines in Loyd & France (2014), where variability from 1%–41% is measured. The number and cadence of our observations prevent us from determining the cause of Ross 1044’s variability (e.g., rotational modulations, flares). A dedicated monitoring campaign could pinpoint the cause of this variability.

5.2. Ly α Correlations

Correlating intrinsic Ly α fluxes with stellar properties gives us insight into the behavior of high-energy emission of stars in various evolutionary and temperature regimes. Relationships between stellar properties and Ly α flux values can also provide a powerful means to predict Ly α fluxes for stars without Ly α observations.

Table 4
Properties of All Stars with Intrinsic Ly α Fluxes

R.A. ($^{\circ}$)	Decl. ($^{\circ}$)	Other Name	Spectral Type	References	T_{eff} (K)	References	Radius $R_{\odot}$	References	Plx ^a (mas)	Ly α (erg cm $^{-2}$ s $^{-1}$)	References	Age (Gyr)	References
New													
317.823653042	+33.524935535	Ross 825	K3	1	4680 $\pm$ 177	19	0.57 $^{+0.15}_{-0.07}$	15	10.17 $\pm$ 0.08	(2.65 $^{+0.38}_{-0.76}$) $\times 10^{-15}$	3	>10	3
225.848498243	+03.785579277	Ross 1044	M0	3	3754 $\pm$ 95	25	0.380 $\pm$ 0.029	25	26.9 $\pm$ 8.4	(2.54 $^{+0.14}_{-0.11}$) $\times 10^{-14}$	3	>10	3
Old													
067.695503172	+16.148537247	SAO 93981	F2	8	6567 $\pm$ 49	26	1.474 $^{+0.058}_{-0.047}$	27	22.12 $\pm$ 0.06	(1.41 $\pm$ 0.28) $\times 10^{-12}$	63	1.16 $\pm$ 0.82	38
...	...	Procyon	F5IV-V	7	6648 $\pm$ 71	21	2.13 $\pm$ 0.07	19	284.56 $\pm$ 1.26	(1.47 $\pm$ 0.03) $\times 10^{-10}$	65	1.97 $^{+0.19}_{-0.23}$	21
066.577555282	+21.470267340	SAO 76609	F8V	9	6376 $\pm$ 80	23	1.30 $\pm$ 0.02	15	20.67 $\pm$ 0.07	(2.70 $\pm$ 0.54) $\times 10^{-13}$	63	0.63 $\pm$ 0.05	41
076.377476718	-57.472196938	ζ Dor	F9V	4	6147 $\pm$ 53	21	1.07 $^{+0.02}_{-0.07}$	15	86.02 $\pm$ 0.15	(7.99 $\pm$ 1.60) $\times 10^{-12}$	63	0.68 $\pm$ 0.47	38
184.446711916	-36.093975066	HR 4657	F9V	4	6258 $\pm$ 39	21	1.096 $\pm$ 0.033	27	44.74 $\pm$ 0.81	(1.28 $\pm$ 0.26) $\times 10^{-12}$	63	1.8 $\pm$ 0.5	37
330.795021930	+18.884241930	V376 Peg	F9V	9	6071 $\pm$ 20	22	1.18 $\pm$ 0.02	15	20.68 $\pm$ 0.05	(1.50 $\pm$ 0.30) $\times 10^{-13}$	63	3.83 $^{+0.98}_{-0.70}$	22
066.900016757	+15.589088762	V993 Tau	G0	8	6197 $\pm$ 94	23	1.27 $^{+0.03}_{-0.02}$	15	20.93 $\pm$ 0.07	(5.90 $\pm$ 1.18) $\times 10^{-13}$	63	0.63 $\pm$ 0.05	41
088.594850554	+20.275864770	χ Ori	G0V	4	5898 $\pm$ 25	17	0.9791 $\pm$ 0.0091	17	113.12 $\pm$ 0.32	(1.27 $\pm$ 0.25) $\times 10^{-11}$	63	0.3 $\pm$ 0.1	37
238.171482022	+42.454228071	χ Her	G0	1	5890 $\pm$ 53	28	1.7090 $\pm$ 0.0200	29	63.16 $\pm$ 0.15	(2.04 $\pm$ 0.41) $\times 10^{-12}$	63	6.85 $^{+0.42}_{-0.50}$	22
271.599395673	-36.019748261	HR 6748	G0V	4	5932 $\pm$ 80	23	0.98 $^{+0.01}_{-0.04}$	15	58.13 $\pm$ 0.12	(3.73 $\pm$ 0.75) $\times 10^{-12}$	63	0.44 $\pm$ 0.19	40
...	...	Sun	G2V	...	5778	...	1.0	...	...	5.95-9.15 ^b	65	4.566 $\pm$ 0.005	66
...	...	α Cen A	G2V	4	5793 $\pm$ 7	17	1.2329 $\pm$ 0.0037	17	754.81 $\pm$ 4.11	(1.01 $\pm$ 0.20) $\times 10^{-10}$	63	5.3 $\pm$ 0.3	34
112.676660493	-37.339135172	HR 2882	G2V	4	5830 $\pm$ 76	22	0.93 $^{+0.02}_{-0.01}$	15	45.93 $\pm$ 0.03	(2.76 $\pm$ 0.55) $\times 10^{-12}$	63	0.35 $\pm$ 0.07	40
168.133469825	+35.813428317	HR 4345	G2	1	5906 $\pm$ 29	28	0.99 $\pm$ 0.03	30	44.14 $\pm$ 0.04	(2.09 $\pm$ 0.42) $\times 10^{-12}$	63	0.45 $\pm$ 0.02	40
049.841563537	+03.370603059	κ Cet	G4	1	5723 $\pm$ 76	17	0.9193 $\pm$ 0.0247	17	109.34 $\pm$ 0.31	(8.44 $\pm$ 1.70) $\times 10^{-12}$	63	0.6 $\pm$ 0.2	22
129.458268090	-06.806694022	SAO 136111	G5V	7	5836 $\pm$ 45	28	1.00 $\pm$ 0.02	15	41.08 $\pm$ 0.04	(1.34 $\pm$ 0.27) $\times 10^{-12}$	63	0.51 $\pm$ 0.14	40
093.438506782	-23.861458285	HR 2225	G6.5V	4	5651 $\pm$ 43	28	0.890 $\pm$ 0.04	18	59.76 $\pm$ 0.02	(3.45 $\pm$ 0.69) $\times 10^{-12}$	63	0.28-0.36	39
199.596454977	-18.315774489	61 Vir	G7V	4	5538 $\pm$ 13	18	0.987 $\pm$ 0.005	18	117.57 $\pm$ 0.24	(1.69 $\pm$ 0.34) $\times 10^{-12}$	63	9.41 $^{+1.31}_{-1.15}$	22
222.848032870	+19.100275013	ξ Boo A	G7V	7	5483 $\pm$ 32	17	0.8627 $\pm$ 0.0107	17	148.52 $\pm$ 0.24	(1.85 $\pm$ 0.37) $\times 10^{-11}$	63	0.2 $\pm$ 0.1	37
001.655138540	+29.020738353	HR 8	G8V	7	5327 $\pm$ 39	17	0.9172 $\pm$ 0.0090	17	72.58 $\pm$ 0.05	(4.77 $\pm$ 0.95) $\times 10^{-12}$	63	0.3 $\pm$ 0.1	22
220.129108915	-16.209576638	SAO 158720	G8V	4	5574 $\pm$ 50	23	0.87 $^{+0.02}_{-0.04}$	15	42.09 $\pm$ 0.04	(1.44 $\pm$ 0.29) $\times 10^{-12}$	63	0.62 $\pm$ 0.07	40
321.170945318	-68.227107394	SAO 254993	G8V	4	5480 $\pm$ 80	23	0.87 $\pm$ 0.01	15	48.06 $\pm$ 0.34	(2.47 $\pm$ 0.49) $\times 10^{-12}$	63	0.33 $\pm$ 0.08	40
026.009302877	-15.933798651	τ Cet	G8.5V	4	5290 $\pm$ 39	17	0.8154 $\pm$ 0.0122	17	277.52 $\pm$ 0.52	(9.99 $\pm$ 2.0) $\times 10^{-12}$	63	5.6 $\pm$ 1.2	37
201.437998838	+56.970541983	SAO 28753	G9V	7	5308 $\pm$ 36	28	0.84 $\pm$ 0.03	30	46.17 $\pm$ 0.02	(1.62 $\pm$ 0.32) $\times 10^{-12}$	63	0.33 $\pm$ 0.10	40
300.182122282	+22.709775924	HD 189733	K2V	7	5019 $\pm$ 23	44	0.76 $\pm$ 0.01	44	50.57 $\pm$ 0.03	(7.48 $\pm$ 1.50) $\times 10^{-13}$	65	6.4 $^{+4.8}_{-4.2}$	30
085.334752342	+53.478804107	HR 1925	K0V	7	5243 $\pm$ 32	28	0.850 $\pm$ 0.050	18	81.43 $\pm$ 0.05	(4.57 $\pm$ 0.91) $\times 10^{-12}$	63	0.5 $\pm$ 0.1	22
063.808266649	-07.667602660	40 Eri A	K0.5V	4	5147 $\pm$ 14	18	0.805 $\pm$ 0.004	18	198.57 $\pm$ 0.51	(6.93 $\pm$ 1.39) $\times 10^{-12}$	63	11.76 $^{+1.92}_{-5.19}$	22
143.181619543	+26.987467661	DX Leo	K1V	4	5315 $\pm$ 35	28	0.81 $\pm$ 0.02	15	55.32 $\pm$ 0.06	(2.31 $\pm$ 0.46) $\times 10^{-12}$	63	0.25 $\pm$ 0.05	43
168.637658369	+25.710596159	HD 97658	K1	7	5157 $\pm$ 29	28	0.72 $\pm$ 0.02	30	46.35 $\pm$ 0.05	(9.1 $^{+9.9}_{-2.3}$) $\times 10^{-13}$	59	9.7 $\pm$ 2.8	44
271.365865680	+02.494347134	70 Oph A	K1	1	5407 $\pm$ 52	18	0.831 $\pm$ 0.004	18	195.22 $\pm$ 0.10	(2.14 $\pm$ 0.43) $\times 10^{-11}$	63	1.3 $\pm$ 0.3	37
289.752832267	+41.631884026	Kepler-444	K1	1	5053 $\pm$ 45	28	0.748 $\pm$ 0.006	24	27.41 $\pm$ 0.03	(5.47 $\pm$ 1.77) $\times 10^{-14}$	60	11.23 $^{+0.91}_{-0.99}$	33
043.135621621	-12.770528318	EP Eri	K1.5V	4	5167 $\pm$ 44	21	0.79 $^{+0.04}_{-0.02}$	15	96.54 $\pm$ 0.04	(6.05 $\pm$ 1.21) $\times 10^{-12}$	63	0.2 $\pm$ 0.1	22
...	...	α Cen B	K2IV	4	5232 $\pm$ 8	17	0.8761 $\pm$ 0.0029	17	796.92 $\pm$ 25.90	(1.50 $\pm$ 0.30) $\times 10^{-10}$	63	5.3 $\pm$ 0.3	34
004.587759006	+30.955409811	PW And	K2V	11	4796 $\pm$ 80	23	0.72 $^{+0.01}_{-0.02}$	15	35.29 $\pm$ 0.05	(2.31 $\pm$ 0.46) $\times 10^{-12}$	63	0.15 $^{+0.05}_{-0.02}$	45
053.228430601	-09.458171515	ϵ Eri	K2V	4	5077 $\pm$ 35	18	0.735 $\pm$ 0.005	18	312.22 $\pm$ 0.47	(6.1 $\pm$ 0.2) $\times 10^{-11}$	59	0.5 $\pm$ 0.1	22
057.604601528	+17.246412457	V471 Tau	K2V	10	5291 $\pm$ 167	27	0.83 $\pm$ 0.03	31	20.96 $\pm$ 0.04	(2.87 $\pm$ 0.57) $\times 10^{-12}$	63	0.63 $\pm$ 0.05	41
143.105446328	-11.184489206	LQ Hya	K2V	12	5376 $\pm$ 43	17	1.0029 $\pm$ 0.0158	17	54.68 $\pm$ 0.07	(4.01 $\pm$ 0.80) $\times 10^{-12}$	63	0.07 $^{+0.03}_{-0.02}$	43
258.834197764	-26.606646978	36 Oph A	K2	1	5103 $\pm$ 29	28	0.76 $\pm$ 0.02	15	167.82 $\pm$ 0.16	(1.42 $\pm$ 0.28) $\times 10^{-11}$	63	1.7 $\pm$ 0.4	22
349.865586265	+79.003831692	V368 Cep	K2V	7	5075 $\pm$ 36	28	0.76 $^{+0.02}_{-0.01}$	15	52.73 $\pm$ 0.03	(2.99 $\pm$ 0.60) $\times 10^{-12}$	63	0.09 $^{+0.06}_{-0.04}$	43
088.517219072	-60.023728916	HD 40307	K2.5V	4	4925 $\pm$ 71	22	0.71 $\pm$ 0.01	15	77.27 $\pm$ 0.03	(2.0 $^{+2.9}_{-0.3}$) $\times 10^{-13}$	59	6.9 $\pm$ 4.0	44
311.937623890	-36.595010211	Speedy Mic	K3V	13	4609 $\pm$ 80	23	1.42 $^{+0.03}_{-0.06}$	15	14.98 $\pm$ 0.27	(1.85 $\pm$ 0.37) $\times 10^{-12}$	63	0.03 $\pm$ 0.01	40
330.871402102	-56.796902312	ϵ Ind	K4V	4	4649 $\pm$ 36	21	0.732 $\pm$ 0.006	32	274.81 $\pm$ 0.25	(3.10 $\pm$ 0.62) $\times 10^{-11}$	63	1.6 $\pm$ 0.2	21
316.747737594	+38.763411107	61 Cyg A	K5	5	4361 $\pm$ 17	18	0.665 $\pm$ 0.005	35	285.95 $\pm$ 0.10	(1.72 $\pm$ 0.34) $\times 10^{-11}$	63	6.0 $\pm$ 1.0	35
147.782122563	-43.504816171	HD 85512	K6V	4	4455 $\pm$ 80	23	0.70 $^{+0.02}_{-0.04}$	15	88.62 $\pm$ 0.04	(1.2 $^{+1.8}_{-0.3}$) $\times 10^{-12}$	59	5.61 $\pm$ 0.61	50
077.958661296	-45.043019828		sdM1	2	3570 $\pm$ 80	20	0.291 $\pm$ 0.025	20	254.23 $\pm$ 0.04	(5.27 $\pm$ 0.26) $\times 10^{-13}$	20	11.5 $^{+0.5}_{-1.5}$	20

Table 4
(Continued)

R.A. (°)	Decl. (°)	Other Name	Spectral Type	References	T_{eff} (K)	References	Radius $R_{\odot}$	References	Plx ^a (mas)	Ly α (erg cm ⁻² s ⁻¹)	References	Age (Gyr)	References
Kapteyn's Star													
311.291136883	-31.342450016	AU Mic	M1	6	3588 ± 87	16	0.698 ± 0.021	16	102.83 ± 0.05	$(1.07 \pm 0.04) \times 10^{-11}$	61	0.02 ± 0.01	45
259.751060918	-34.997765110	GJ 667C	M1.5V	48	3472 ± 73	6	0.37 ± 0.05	6	138.02 ± 0.09	$(5.2 \pm 0.9) \times 10^{-13}$	59	>2	51
323.391261617	-49.012516898	GJ 832	M2	6	3522 ± 60	6	0.442 ± 0.013	16	201.40 ± 0.04	$(9.5 \pm 0.6) \times 10^{-13}$	59	8.4	46
070.735385329	+18.953357960	GJ 176	M2	6	3679 ± 77	18	0.453 ± 0.022	18	105.56 ± 0.07	$(3.9 \pm 0.2) \times 10^{-13}$	59	4.0 ± 0.3	18
154.898887344	+19.869815836	AD Leo	M3	6	3308 ± 84	16	0.422 ± 0.013	16	201.37 ± 0.07	$(8.07 \pm 0.20) \times 10^{-12}$	61	0.025–0.3	36
175.550536327	+26.703066902	GJ 436	M3	6	3416 ± 53	18	0.455 ± 0.018	18	102.50 ± 0.09	$(2.1 \pm 0.3) \times 10^{-13}$	59	4.2 ± 0.3	18
229.856472500	-07.722693495	GJ 581	M3	6	3415 ± 87	16	0.330 ± 0.01	16	158.75 ± 0.05	$(1.1^{+0.3}_{-0.2}) \times 10^{-12}$	59	4.1 ± 0.3	18
258.831399085	+04.960679473	GJ 1214	M4V	49	3008 ± 96	16	0.203 ± 0.008	16	68.27 ± 0.17	$(1.3^{+1.4}_{-0.5}) \times 10^{-14}$	59	5–10	52
343.323973712	-14.266595816	GJ 876	M4	6	3129 ± 19	18	0.376 ± 0.006	18	213.87 ± 0.08	$(3.9 \pm 0.4) \times 10^{-13}$	59	9.51 ± 0.58	47
153.709069589	-47.154935771	GJ 1132	M4	1	3216 ± 100	16	0.217 ± 0.008	16	79.25 ± 0.04	$(2.9^{+0.4}_{-0.3}) \times 10^{-14}$	64	>5.0	62
341.702962603	+44.332017083	EV Lac	M5	6	3273 ± 86	16	0.341 ± 0.010	16	198.01 ± 0.04	$(2.75 \pm 0.55) \times 10^{-12}$	63	0.025–0.3	36
217.393465743	-62.676182103	Prox Cen	M5.5	14	2840 ± 88	16	0.154 ± 0.005	16	768.50 ± 0.20	$(4.37 \pm 0.07) \times 10^{-12}$	61	5.3 ± 0.3	34
346.626391870	-05.043461802	Trappist-1	M8	53	2550 ± 55	53	0.117 ± 0.004	53	80.45 ± 0.12	$(7.5 \pm 2.3) \times 10^{-15}$	53	7.6 ± 2.2	54
278.907460881	+32.994892032	LSR	M8.5	55	2578 ± 39	56	0.137 ± 0.007	57	175.82 ± 0.09	$(7.0 \pm 3.5) \times 10^{-15}$	58	...	...
J1835+3259													

Notes.

^a All parallaxes come from *Gaia* (Gaia Collaboration et al. 2016, 2018) with the following exceptions: Procyon, α Cen A, α Cen B, and HR 4657 (van Leeuwen 2007), and Ross 1044 (Finch & Zacharias 2016).

^b The Ly α flux range given for the Sun encompasses both the active and quiet Sun values given in Linsky et al. (2013).

References. (1) Bidelman (1985); (2) Hawley et al. (1996); (3) This work; (4) Gray et al. (2006); (5) Alonso-Floriano et al. (2015); (6) Gaidos et al. (2014); (7) Gray et al. (2003); (8) Cayrel de Strobel et al. (2001); (9) Gray et al. (2001); (10) Hussain et al. (2006); (11) Zuckerman & Song (2004); (12) Rice & Strassmeier (1998); (13) Torres et al. (2006); (14) Bessell (1991); (15) Gaia Collaboration et al. (2018); (16) Muirhead et al. (2018); (17) Boyajian et al. (2013); (18) Yee et al. (2017); (19) Stassun et al. (2018); (20) Guinan et al. (2016); (21) Ramírez et al. (2013); (22) Aguilera-Gómez et al. (2018); (23) Casagrande et al. (2011); (24) Silva Aguirre et al. (2015); (25) Newton et al. (2015); (26) Cummings et al. (2017); (27) Huber et al. (2016); (28) Luck (2017); (29) Valenti & Fischer (2005); (30) Brewer et al. (2016); (31) Bochanski et al. (2018); (32) Chen & Kipping (2017); (33) Campante et al. (2015); (34) Joyce & Chaboyer (2018); (35) Kervella et al. (2008); (36) Shkolnik et al. (2009); (37) Ramírez et al. (2012); (38) Pace (2013); (39) Eiroa et al. (2013); (40) Plavchan et al. (2009); (41) Perryman et al. (1998); (42) del Burgo & Allende Prieto (2016); (43) Meshkat et al. (2017); (44) Bonfanti et al. (2016); (45) Bell et al. (2015); (46) Bryden et al. (2009); (47) Mann et al. (2015); (48) Lurie et al. (2014); (49) Newton et al. (2014); (50) Pepe et al. (2011); (51) Anglada-Escudé et al. (2013); (52) Lalitha et al. (2014); (53) Bourrier et al. (2017b); (54) Burgasser & Mamajek (2017); (55) Reid et al. (2003); (56) Rojas-Ayala et al. (2012); (57) Dittmann et al. (2014); (58) Saur et al. (2018); (59) Youngblood et al. (2016); (60) Bourrier et al. (2017a); (61) Youngblood et al. (2017); (62) Berta-Thompson et al. (2015); (63) Wood et al. (2005); (64) Waalkes et al. (2019); (65) Linsky et al. (2013); (66) Bahcall et al. (1995).

Figure 3. Left: $\text{Ly}\alpha$ Flux at 1 au vs. T_{eff} for all objects in Table 4. Young stars (age <1 Gyr) are plotted in light blue, while old stars (age >1 Gyr) are plotted in yellow. Ross 825 and Ross 1044 (age >10 Gyr) are plotted in red. Two additional symbols are plotted for Ross 1044 representing the maximum and minimum variability determined in Section 5.1. The two solar symbols represent values for the quiet and active Sun from Linsky et al. (2013). The solid black line represents the best fit to the data, with red lines showing individual fits from a Monte Carlo analysis. Right: same as the left panel, but with $\text{Ly}\alpha$ fluxes scaled to the distance to the habitable zone for each star.

Table 5
GALEX NUV and $\text{Ly}\alpha$ Fluxes for M Dwarfs and Young K Dwarfs

Name	Spectral Type	Age (Gyr)	Plx ^a (mas)	$\text{Ly}\alpha$ ($\text{erg cm}^{-2} \text{s}^{-1}$)	NUV (mag)
PW And	K2	$0.15^{+0.05}_{-0.02}$	35.29 ± 0.05	$(2.31 \pm 0.46) \times 10^{-12}$	15.317 ± 0.012
Speedy Mic	K3	0.03 ± 0.01	14.98 ± 0.27	$(1.85 \pm 0.37) \times 10^{-12}$	15.469 ± 0.009
Ross 1044	M0	>10	26.9 ± 8.4	$(2.54^{+0.14}_{-0.11}) \times 10^{-14}$	21.571 ± 0.095
Kapteyn's Star	sdM1	$11.5^{+0.5}_{-1.5}$	254.23 ± 0.03	$(5.27 \pm 0.26) \times 10^{-13}$	19.103 ± 0.048
AU Mic	M1	0.02 ± 0.01	102.83 ± 0.05	$(1.07 \pm 0.04) \times 10^{-11}$	15.614 ± 0.010
GJ 832	M2	8.4	201.41 ± 0.04	$(9.5 \pm 0.6) \times 10^{-13}$	18.393 ± 0.036
GJ 176	M2	4.0 ± 0.3	105.56 ± 0.07	$(3.9 \pm 0.2) \times 10^{-13}$	18.825 ± 0.052
GJ 436	M3	4.2 ± 0.3	102.50 ± 0.09	$(2.1 \pm 0.3) \times 10^{-13}$	20.685 ± 0.198
AD Leo	M3	$0.025-0.3$	201.37 ± 0.07	$(8.07 \pm 0.20) \times 10^{-12}$	15.814 ± 0.017
GJ 876	M4	9.51 ± 0.58	213.87 ± 0.08	$(3.9 \pm 0.4) \times 10^{-13}$	20.149 ± 0.087
Prox Cen	M5.5	5.3 ± 0.3	768.50 ± 0.20	$(4.37 \pm 0.07) \times 10^{-12}$	18.601 ± 0.086

Note.

^a Parallaxes from *Gaia* (Gaia Collaboration et al. 2016, 2018), with the exception of Ross 1044 (Finch & Zacharias 2016).

5.2.1. $\text{Ly}\alpha$ Behavior with Effective Temperature

Linsky et al. (2013) showed a correlation between stellar effective temperature (T_{eff}) and $\text{Ly}\alpha$ flux. We revisit this relationship here to include additional measurements published since that paper as well as Ross 825 and Ross 1044. These additions increase the entire sample size by $\sim 30\%$, with 47 $\text{Ly}\alpha$ measurements used in Linsky et al. (2013) and 61 used in this work, two of which are new measurements. We also use updated T_{eff} measurements as well as more precise parallaxes from *Gaia* DR2 (Gaia Collaboration et al. 2016, 2018). Table 4 lists these properties (T_{eff} , age, parallax) and intrinsic $\text{Ly}\alpha$ fluxes for all stars with $\text{Ly}\alpha$ flux measurements. For Kapteyn's star, Guinan et al. (2016) directly measured a $\text{Ly}\alpha$ flux of $5.32 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$, though no uncertainty is provided for this measurement. We assume an uncertainty of 5% for this directly measured line.

Figure 3 shows the $\text{Ly}\alpha$ flux for each star in Table 4 scaled to 1 au versus their effective temperatures. While Linsky et al. (2013) partition different stellar samples based on their rotation rates, we instead choose to use age because age measurements are more readily available for this sample. We note that determining precise stellar ages is a challenging process, and many different methods can be used depending on the star in question and the data available for that star. All ages used in this work are provided in Table 4. For more information on how a particular age was determined, please refer to the reference provided in the table. There is a clear difference between young (<1 Gyr) and old (>1 Gyr) samples in Figure 3. $\text{Ly}\alpha$ emission is typically much stronger from young stars than old stars with similar T_{eff} values. For old stars, a very clear trend of decreasing $\text{Ly}\alpha$ flux strength with decreasing T_{eff} can be seen. We fit this trend using a least-squares optimization

Figure 4. Left: $\text{Ly}\alpha$ flux vs. *GALEX* NUV flux for low-mass stars (light blue symbols) and our new measurement for Ross 1044 (red symbol). Two additional symbols are plotted for Ross 1044 representing the maximum and minimum variability determined in Section 5.1. The solid black line represents the best fit to the data, with red lines showing individual fits from a Monte Carlo analysis. Right: same as left panel, but for *GALEX* FUV.

Table 6
GALEX FUV and $\text{Ly}\alpha$ Fluxes for K and M Dwarfs

Name	Spectral Type	Age (Gyr)	Plx (mas)	$\text{Ly}\alpha$ ($\text{erg cm}^{-2} \text{s}^{-1}$)	FUV (mag)
DX Leo	K0	0.25 ± 0.05	55.32 ± 0.06	$(2.31 \pm 0.46) \times 10^{-12}$	18.188 ± 0.053
HR 1925	K1	0.5 ± 0.1	81.43 ± 0.05	$(4.57 \pm 0.91) \times 10^{-12}$	18.695 ± 0.091
HD 97658	K1	9.7 ± 2.8	46.35 ± 0.05	$(9.1^{+9.9}_{-4.5}) \times 10^{-13}$	21.568 ± 0.308
EP Eri	K2	0.2 ± 0.1	96.54 ± 0.04	$(6.05 \pm 1.21) \times 10^{-12}$	17.779 ± 0.018
ϵ Eri	K2	0.5 ± 0.1	312.22 ± 0.47	$(6.1 \pm 0.2) \times 10^{-11}$	16.049 ± 0.023
LQ Hya	K2	$0.07^{+0.03}_{-0.02}$	54.68 ± 0.07	$(4.01 \pm 0.80) \times 10^{-12}$	17.217 ± 0.037
HD 40307	K2.5	6.9 ± 4.0	77.27 ± 0.03	$(2.0^{+2.2}_{-0.9}) \times 10^{-13}$	21.728 ± 0.346
Speedy Mic	K3	0.03 ± 0.01	14.98 ± 0.27	$(1.85 \pm 0.37) \times 10^{-12}$	18.604 ± 0.079
ϵ Ind	K5	1.6 ± 0.2	274.80 ± 0.25	$(3.10 \pm 0.62) \times 10^{-11}$	17.881 ± 0.047
AU Mic	M1	0.02 ± 0.01	102.83 ± 0.05	$(1.07 \pm 0.04) \times 10^{-11}$	17.436 ± 0.038
GJ 832	M2	8.4	201.41 ± 0.04	$(9.5 \pm 0.6) \times 10^{-13}$	20.687 ± 0.168
GJ 176	M2	4.0 ± 0.3	105.56 ± 0.07	$(3.9 \pm 0.2) \times 10^{-13}$	21.130 ± 0.347
GJ 876	M4	9.51 ± 0.58	213.87 ± 0.08	$(3.9 \pm 0.4) \times 10^{-13}$	22.560 ± 0.360

approach, with uncertainties handled in a Monte Carlo fashion. We find

$$\log_{10}(F_{\text{Ly}\alpha})_{1 \text{ au}} = (6.754 \pm 0.263) \times 10^{-4}(T_{\text{eff}}) - 2.639 \pm 0.137. \quad (1)$$

The rms scatter about the fit is ~ 0.21 dex. We also plot in Figure 3 the $\text{Ly}\alpha$ flux scaled to the HZ for each target. The distance to the HZ for each star is calculated using their effective temperatures and radii listed in Table 4 and Equations (4) and (5) of Kopparapu et al. (2013a) and the updated coefficients in Kopparapu et al. (2013b). The HZ distance is taken as the average value between the distances to the moist greenhouse and maximum greenhouse boundaries. While the relation between $\text{Ly}\alpha$ flux and T_{eff} flattens out for this sample, it is notable that the slope of this relation is positive, implying that, in general, the $\text{Ly}\alpha$ flux in the HZ increases with decreasing T_{eff} . The relationship between $\text{Ly}\alpha$

HZ flux and T_{eff} is

$$\log_{10}(F_{\text{Ly}\alpha})_{\text{HZ}} = (-1.601 \pm 0.243) \times 10^{-4}(T_{\text{eff}}) + 1.804 \pm 0.126. \quad (2)$$

The rms scatter about the fit is ~ 0.19 dex.

5.2.2. Predicting $\text{Ly}\alpha$ Fluxes with *GALEX* Photometry

Because $\text{Ly}\alpha$ emission is impossible to measure directly for almost all stars, and even indirect methods, such as reconstructions, require valuable *HST* time, correlations between $\text{Ly}\alpha$ fluxes and other activity indicators are immensely valuable as predictive tools. Shkolnik et al. (2014) used *GALEX* photometry and reconstructed $\text{Ly}\alpha$ emission profiles from Wood et al. (2005), France et al. (2012, 2013), and Linsky et al. (2013) to show trends between NUV and FUV photometry and the reconstructed $\text{Ly}\alpha$ fluxes for K and M dwarfs. We update these correlations with precision parallaxes

from *Gaia* and new and updated $\text{Ly}\alpha$ fluxes from this work, Guinan et al. (2016), Youngblood et al. (2016), and Youngblood et al. (2017). The new NUV relation contains three objects not included in the Shkolnik et al. (2014) relation; Ross 1044, Kapteyn’s Star, and GJ 176. We also produce these new correlations using flux at 1 au instead of excess surface flux as in Shkolnik et al. (2014), which avoids any uncertainties from model photospheric flux and radius estimates. Thus for the NUV relation, we only include stars where the photospheric NUV flux is negligible, namely, M stars (at all ages) and young K stars (Schneider & Shkolnik 2018; Richey-Yowell et al. 2019).

Table 5 summarizes all observed $\text{Ly}\alpha$ flux measurements for M stars and young K stars with NUV detections in *GALEX*. Note that there are many young K dwarfs from Table 5 that were observed by *GALEX*; however, the majority of the sources were saturated ($\text{NUV} < 15$ mag), and are thus not included here. For objects that have detections from multiple *GALEX* surveys, the magnitudes presented in Tables 5 and 6 are the weighted average of their flux densities, converted back to magnitude. Figure 4 shows a comparison of the the $\text{Ly}\alpha$ flux values versus *GALEX* NUV flux values at 1 au. We perform a least-squares fit to the data and find the following relation between $\text{Ly}\alpha$ flux and *GALEX* NUV fluxes:

$$\log_{10}(F_{\text{Ly}\alpha}) = (0.701 \pm 0.019) * \log_{10}(F_{\text{NUV}}) + 0.193 \pm 0.043. \quad (3)$$

Uncertainties for the fit are determined in a Monte Carlo fashion. The rms scatter about this fit is 0.10 dex.

Some nearby, low-mass stars are too bright for reliable *GALEX* NUV measurements. For these stars, it may be possible to use FUV fluxes. We plot *GALEX* FUV fluxes versus $\text{Ly}\alpha$ fluxes in Figure 4, with FUV data given in Table 6. All K and M dwarfs with unsaturated *GALEX* FUV measurements are included in the FUV relation, with the total number of stars used increasing from 10 in Shkolnik et al. (2014) to 13 in this work with the addition of HD 97658, HD 40307, and GJ 176. We perform a fit using the same methods as for *GALEX* NUV data and find

$$\log_{10}(F_{\text{Ly}\alpha}) = (0.742 \pm 0.038) * \log_{10}(F_{\text{FUV}}) + 0.945 \pm 0.053. \quad (4)$$

The rms scatter about this fit is 0.13 dex. The utility of these correlations can be far-reaching, as *GALEX* has archived flux measurements for thousands of late-K and M dwarfs in the solar neighborhood (e.g., Ansdell et al. 2015; Jones & West 2016; Kastner et al. 2017; Miles & Shkolnik 2017; Schneider & Shkolnik 2018; Richey-Yowell et al. 2019).

6. Conclusion

We presented *HST*/STIS observations of Ross 1044 and Ross 825, two low-mass stars with sufficient RVs to directly observe the majority of each star’s intrinsic $\text{Ly}\alpha$ flux ($\sim 74\%$ for Ross 1044 and $\sim 63\%$ for Ross 825). We combined these new $\text{Ly}\alpha$ measurements with updated astrometric information and physical parameters to explore the relationship between $\text{Ly}\alpha$ flux and T_{eff} . We also constructed new correlations between $\text{Ly}\alpha$ fluxes and *GALEX* UV photometry.

Astrometric missions such as *Gaia* will soon reveal numerous additional nearby stars with radial velocities for which such observations are possible. High-RV targets are the only way to directly observe the majority of the $\text{Ly}\alpha$ flux from low-mass stars. While the exact RV value needed depends on a

target’s distance and the ISM properties toward that target, a minimum absolute value of $\sim 100 \text{ km s}^{-1}$, corresponding to a wavelength shift of $\approx 0.4 \text{ \AA}$, is likely necessary. Of the $\sim 73,000$ stars within 50 pc with RV measurements in the *Gaia* DR2 catalog, only 120 (0.16%) have radial velocities $> 100 \text{ km s}^{-1}$. Each of these objects are thus invaluable as laboratories for investigating the UV environments of nearby stars.

This work is based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program #15283. Support for program #15283 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. A.S. and E.S. appreciate support from NASA/Habitable Worlds grant NNX16AB62G. T.B. was supported in part by NASA *HST* grant HST-AR-13911 and NASA Habitable Worlds grant NNX16AB62G. This work is based on observations made with the NASA *Galaxy Evolution Explorer*. *GALEX* is operated for NASA by the California Institute of Technology under NASA contract NAS 5-98034. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

Software: emcee (Foreman-Mackey et al. 2013).

ORCID iDs

Adam C. Schneider <https://orcid.org/0000-0002-6294-5937>

Evgenya L. Shkolnik <https://orcid.org/0000-0002-7260-5821>

Travis S. Barman <https://orcid.org/0000-0002-7129-3002>

R. Parke Loyd <https://orcid.org/0000-0001-5646-6668>

References

- Aguilera-Gómez, C., Ramírez, I., & Chanamé, J. 2018, *A&A*, **614**, A55
- Alonso-Floriano, F. J., Morales, J. C., Caballero, J. A., et al. 2015, *A&A*, **577**, A128
- Anglada-Escudé, G., Tuomi, M., Gerlach, E., et al. 2013, *A&A*, **556**, A126
- Ansdell, M., Gaidos, E., Mann, A. W., et al. 2015, *ApJ*, **798**, 41
- Arney, G. N. 2019, *ApJL*, **873**, L7
- Bahcall, J. N., Pinsonneault, M. H., & Wasserburg, G. J. 1995, *RvMP*, **67**, 781
- Bell, C. P. M., Mamajek, E. E., & Naylor, T. 2015, *MNRAS*, **454**, 593
- Berta-Thompson, Z. K., Irwin, J., Charbonneau, D., et al. 2015, *Natur*, **527**, 204
- Bessell, M. S. 1991, *AJ*, **101**, 662
- Bidelman, W. P. 1985, *ApJS*, **59**, 197
- Bochanski, J. J., Faherty, J. K., Gagné, J., et al. 2018, *AJ*, **155**, 149
- Bochanski, J. J., Hawley, S. L., Covey, K. R., et al. 2010, *AJ*, **139**, 2679
- Bonfanti, A., Ortolani, S., & Nascimbeni, V. 2016, *A&A*, **585**, A5
- Bourrier, V., Ehrenreich, D., Allart, R., et al. 2017a, *A&A*, **602**, A106
- Bourrier, V., Ehrenreich, D., & Lecavelier des Etangs, A. 2015, *A&A*, **582**, A65
- Bourrier, V., Ehrenreich, D., Wheatley, P. J., et al. 2017b, *A&A*, **599**, L3
- Boyajian, T. S., von Braun, K., van Belle, G., et al. 2013, *ApJ*, **771**, 40
- Brewer, J. M., Fischer, D. A., Valenti, J. A., et al. 2016, *ApJS*, **225**, 32
- Brown, T. M., Charbonneau, D., Gilliland, R. L., et al. 2001, *ApJ*, **552**, 699
- Bryden, G., Beichman, C. A., Carpenter, J. M., et al. 2009, *ApJ*, **705**, 1226
- Burgasser, A. J., & Mamajek, E. E. 2017, *ApJ*, **845**, 110

- Campante, T. L., Barclay, T., Swift, J. J., et al. 2015, *ApJ*, 799, 170
- Carney, B. W., & Latham, D. W. 1987, *AJ*, 93, 116
- Casagrande, L., Schönrich, R., Asplund, M., et al. 2011, *A&A*, 530, A138
- Cayrel de Strobel, G., Soubiran, C., & Ralite, N. 2001, *A&A*, 373, 159
- Chen, J., & Kipping, D. 2017, *ApJ*, 834, 17
- Cummings, J. D., Deliyannis, C. P., Maderak, R. M., et al. 2017, *AJ*, 153, 128
- Cuntz, M., & Guinan, E. F. 2016, *ApJ*, 827, 79
- del Burgo, C., & Allende Prieto, C. 2016, *MNRAS*, 463, 1400
- Dittmann, J. A., Irwin, J. M., Charbonneau, D., & Berta-Thompson, Z. K. 2014, *ApJ*, 784, 156
- Domagal-Goldman, S. D., Segura, A., Claire, M. W., Robinson, T. D., & Meadows, V. S. 2014, *ApJ*, 792, 90
- Dotter, A., Conroy, C., Cargile, P., & Asplund, M. 2017, *ApJ*, 840, 99
- Dressing, C. D., & Charbonneau, D. 2015, *ApJ*, 807, 45
- Dupuy, T. J., Kratter, K. M., Kraus, A. L., et al. 2016, *ApJ*, 817, 80
- Eiroa, C., Marshall, J. P., Mora, A., et al. 2013, *A&A*, 555, A11
- Finch, C. T., & Zacharias, N. 2016, *AJ*, 151, 160
- Fontenla, J. M., Linsky, J. L., Witbrod, J., et al. 2016, *ApJ*, 830, 154
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, 125, 306
- France, K., Froning, C. S., Linsky, J. L., et al. 2013, *ApJ*, 763, 149
- France, K., Linsky, J. L., Tian, F., Froning, C. S., & Roberge, A. 2012, *ApJL*, 750, L32
- France, K., Loyd, R. O. P., Youngblood, A., et al. 2016, *ApJ*, 820, 89
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, *A&A*, 616, A1
- Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, *A&A*, 595, A1
- Gaidos, E., Mann, A. W., Lépine, S., et al. 2014, *MNRAS*, 443, 2561
- Gray, R. O., Corbally, C. J., Garrison, R. F., et al. 2003, *AJ*, 126, 2048
- Gray, R. O., Corbally, C. J., Garrison, R. F., et al. 2006, *AJ*, 132, 161
- Gray, R. O., Napier, M. G., & Winkler, L. I. 2001, *AJ*, 121, 2148
- Guinan, E. F., Engle, S. G., & Durbin, A. 2016, *ApJ*, 821, 81
- Hardegree-Ullman, K. K., Cushing, M. C., Muirhead, P. S., et al. 2019, *AJ*, 158, 75
- Harman, C. E., Schwieterman, E. W., Schottelkotte, J. C., & Kasting, J. F. 2015, *ApJ*, 812, 137
- Hawley, S. L., Gizis, J. E., & Reid, I. N. 1996, *AJ*, 112, 2799
- Hébrard, G., & Moos, H. W. 2003, *ApJ*, 599, 297
- Heller, R., & Armstrong, J. 2014, *AsBio*, 14, 50
- Hu, R., Seager, S., & Bains, W. 2012, *ApJ*, 761, 166
- Huber, D., Bryson, S. T., Haas, M. R., et al. 2016, *ApJS*, 224, 2
- Hussain, G. A. J., Allende Prieto, C., Saar, S. H., et al. 2006, *MNRAS*, 367, 1699
- Jones, D. O., & West, A. A. 2016, *ApJ*, 817, 1
- Joyce, M., & Chaboyer, B. 2018, *ApJ*, 864, 99
- Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, *Icar*, 101, 108
- Kastner, J. H., Sacco, G., Rodriguez, D., et al. 2017, *ApJ*, 841, 73
- Kervella, P., Mérand, A., Pichon, B., et al. 2008, *A&A*, 488, 667
- Kopparapu, R. K., Ramirez, R., Kasting, J. F., et al. 2013a, *ApJ*, 765, 131
- Kopparapu, R. K., Ramirez, R., Kasting, J. F., et al. 2013b, *ApJ*, 770, 82
- Lalitha, S., Poppenhaeger, K., Singh, K. P., Czesla, S., & Schmitt, J. H. M. M. 2014, *ApJL*, 790, L11
- Lichtenegger, H. I. M., Lammer, H., Grießmeier, J.-M., et al. 2010, *Icar*, 210, 1
- Lindgren, L., Hernández, J., Bombrun, A., et al. 2018, *A&A*, 616, A2
- Linsky, J. L., Draine, B. T., Moos, H. W., et al. 2006, *ApJ*, 647, 1106
- Linsky, J. L., France, K., & Ayres, T. 2013, *ApJ*, 766, 69
- Loyd, R. O. P., & France, K. 2014, *ApJS*, 211, 9
- Loyd, R. O. P., France, K., Youngblood, A., et al. 2016, *ApJ*, 824, 102
- Luck, R. E. 2017, *AJ*, 153, 21
- Luger, R., & Barnes, R. 2015, *AsBio*, 15, 119
- Lurie, J. C., Henry, T. J., Jao, W.-C., et al. 2014, *AJ*, 148, 91
- Mann, A. W., Feiden, G. A., Gaidos, E., et al. 2015, *ApJ*, 804, 64
- Meshkat, T., Mawet, D., Bryan, M. L., et al. 2017, *AJ*, 154, 245
- Miles, B. E., & Shkolnik, E. L. 2017, *AJ*, 154, 67
- Muirhead, P. S., Dressing, C. D., Mann, A. W., et al. 2018, *AJ*, 155, 180
- Mulders, G. D., Pascucci, I., & Apai, D. 2015, *ApJ*, 798, 112
- Newton, E. R., Charbonneau, D., Irwin, J., et al. 2014, *AJ*, 147, 20
- Newton, E. R., Charbonneau, D., Irwin, J., et al. 2015, *ApJ*, 800, 85
- Pace, G. 2013, *A&A*, 551, L8
- Peacock, S., Barman, T., Shkolnik, E. L., et al. 2019, *ApJ*, 871, 235
- Pecat, M. J., & Mamajek, E. E. 2013, *ApJS*, 208, 9
- Pepe, F., Lovis, C., Ségransan, D., et al. 2011, *A&A*, 534, A58
- Perryman, M. A. C., Brown, A. G. A., Lebreton, Y., et al. 1998, *A&A*, 331, 81
- Plavchan, P., Werner, M. W., Chen, C. H., et al. 2009, *ApJ*, 698, 1068
- Ramírez, I., Allende Prieto, C., & Lambert, D. L. 2013, *ApJ*, 764, 78
- Ramírez, I., Fish, J. R., Lambert, D. L., et al. 2012, *ApJ*, 756, 46
- Rauer, H., Catala, C., Aerts, C., et al. 2014, *ExA*, 38, 249
- Redfield, S., & Linsky, J. L. 2008, *ApJ*, 673, 283
- Reid, I. N., Cruz, K. L., Laurie, S. P., et al. 2003, *AJ*, 125, 354
- Reid, I. N., Hawley, S. L., & Gizis, J. E. 1995, *AJ*, 110, 1838
- Rice, J. B., & Strassmeier, K. G. 1998, *A&A*, 336, 972
- Richey-Yowell, T., Shkolnik, E. L., Schneider, A. C., et al. 2019, *ApJ*, 872, 17
- Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, *JATIS*, 1, 014003
- Rojas-Ayala, B., Covey, K. R., Muirhead, P. S., et al. 2012, *ApJ*, 748, 93
- Ross, F. E. 1929, *AJ*, 39, 140
- Ross, F. E. 1939, *AJ*, 48, 163
- Rugheimer, S., Kaltenegger, L., Segura, A., Linsky, J., & Mohanty, S. 2015, *ApJ*, 809, 57
- Saur, J., Fischer, C., Wennmacher, A., et al. 2018, *ApJ*, 859, 74
- Schneider, A. C., & Shkolnik, E. L. 2018, *AJ*, 155, 122
- Schuster, W. J., Moitinho, A., Márquez, A., Parrao, L., & Covarrubias, E. 2006, *A&A*, 445, 939
- Segura, A., Walkowicz, L. M., Meadows, V., Kasting, J., & Hawley, S. 2010, *AsBio*, 10, 751
- Shkolnik, E., Liu, M. C., & Reid, I. N. 2009, *ApJ*, 699, 649
- Shkolnik, E. L., Anglada-Escudé, G., Liu, M. C., et al. 2012, *ApJ*, 758, 56
- Shkolnik, E. L., Rolph, K. A., Peacock, S., & Barman, T. S. 2014, *ApJL*, 796, L20
- Silva Aguirre, V., Davies, G. R., Basu, S., et al. 2015, *MNRAS*, 452, 1227
- Sing, D. K., Vidal-Madjar, A., Désert, J.-M., et al. 2008, *ApJ*, 686, 658
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163
- Stassun, K. G., Oelkers, R. J., Pepper, J., et al. 2018, *AJ*, 156, 102
- Tian, F., France, K., Linsky, J. L., Mauas, P. J. D., & Vieytes, M. C. 2014, *E&PSL*, 385, 22
- Torres, C. A. O., Quast, G. R., da Silva, L., et al. 2006, *A&A*, 460, 695
- Tuomi, M., Jones, H. R. A., Anglada-Escudé, G., et al. 2019, arXiv:1906.04644
- Valenti, J. A., & Fischer, D. A. 2005, *ApJS*, 159, 141
- van Altena, W. F., Lee, J. T., & Hoffleit, E. D. 1995, The General Catalogue of Trigonometric Stellar Parallaxes (New Haven, CT: Yale Univ. Press)
- van Leeuwen, F. 2007, *A&A*, 474, 653
- Waalkes, W. C., Berta-Thompson, Z., Bourrier, V., et al. 2019, *AJ*, 158, 50
- Wood, B. E., Redfield, S., Linsky, J. L., Müller, H.-R., & Zank, G. P. 2005, *ApJS*, 159, 118
- Yee, S. W., Petigura, E. A., & von Braun, K. 2017, *ApJ*, 836, 77
- Youngblood, A., France, K., Loyd, R. O. P., et al. 2016, *ApJ*, 824, 101
- Youngblood, A., France, K., Loyd, R. O. P., et al. 2017, *ApJ*, 843, 31
- Zuckerman, B., & Song, I. 2004, *ARA&A*, 42, 685