PREDICTING Ly$\alpha$ AND Mg II FLUXES FROM K AND M DWARFS USING GALAXY EVOLUTION EXPLORER ULTRAVIOLET PHOTOMETRY* 

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ABSTRACT

A star’s ultraviolet (UV) emission can greatly affect the atmospheric chemistry and physical properties of closely orbiting planets with the potential for severe mass loss. In particular, the Ly$\alpha$ emission line at 1216 Å, which dominates the far-ultraviolet (FUV) spectrum, is a major source of photodissociation of important atmospheric molecules such as water and methane. The intrinsic flux of Ly$\alpha$, however, cannot be directly measured due to the absorption of neutral hydrogen in the interstellar medium and contamination by geocoronal emission. To date, reconstruction of the intrinsic Ly$\alpha$ line based on Hubble Space Telescope spectra has been accomplished for 46 FGKM nearby stars, 28 of which have also been observed by the Galaxy Evolution Explorer (GALEX). Our investigation provides a correlation between published intrinsic Ly$\alpha$ and GALEX far- and near-ultraviolet (NUV) chromospheric fluxes for K and M stars. The negative correlations between the ratio of the Ly$\alpha$ to the GALEX fluxes reveal how the relative strength of Ly$\alpha$ compared to the broadband fluxes weakens as the FUV and NUV excess flux increases. We also correlate GALEX fluxes with the strong NUV Mg II h + k spectral emission lines formed at lower chromospheric temperatures than Ly$\alpha$. The reported correlations provide estimates of intrinsic Ly$\alpha$ and Mg II fluxes for the thousands of K and M stars in the archived GALEX all-sky surveys. These will constrain new stellar upper atmosphere models for cool stars and provide realistic inputs to models describing exoplanetary photochemistry and atmospheric evolution in the absence of UV spectroscopy.

Key words: planet–star interactions – stars: activity – stars: atmospheres – stars: chromospheres

Online-only material: color figures

1. INTRODUCTION

Radial velocity, transit, and imaging methods have enabled the discovery of a variety of exoplanets ranging from hot super-Earths to cold Jupiters, including confirmed terrestrial exoplanets within the habitable zone (HZ; Kasting et al. 1993) around low-mass stars. For giant and terrestrial planets alike, incident stellar emission at short wavelengths ($\lambda < 3000$ Å) affects the chemistry and evolution of an exoplanet’s atmosphere. In particular, it is the high energy of the far-ultraviolet (FUV) radiation that controls the processes of molecular photodissociation and photoionization in the planetary atmosphere (Hu et al. 2012), breaking apart important molecules such as water, methane, and carbon dioxide, and potentially leading to significant mass loss. The possibility of complete evaporation of the planet atmosphere due to high UV (and corresponding particle) flux may explain the high fraction of hot dense planets around cool stars in the current exoplanet population (e.g., Wu & Lithwick 2013; Lammer et al. 2007). In the case of HZ planets, the incident UV stellar flux may also destroy biosignatures with which we hope to detect life and/or produce false-positive biosignatures in the form of abiotic oxygen and ozone (Tian et al. 2014).

Much of the stellar UV flux is emitted from the upper atmospheres of FGKM stars, namely, the chromosphere, transition region, and corona, and measurements at these short wavelengths require space-borne observatories and stars that are bright and not too distant from Earth. The FUV spectrum is dominated by Ly$\alpha$, the resonance line of hydrogen at 1216 Å, which is emitted from the upper chromosphere and lower transition region temperatures of roughly 8000–30,000 K (Fontenla et al. 1988). Linsky et al. (2013) recently highlighted the potential importance of the Ly$\alpha$ emission line to the atmospheres of close-in planets. For example, the Sun’s Ly$\alpha$ contributes $\sim 20\%$ of the total flux between 1 and 1700 Å (Ribas et al. 2005), and is shown to be responsible for more than 50% of the photodissociation rate of the Earth’s H$_2$O and CH$_4$. Ly$\alpha$’s fractional flux increases for cooler stars as the photospheric contribution decreases (Figure 1, right) and can reach up to $\sim 70\%$ of the total FUV flux for late M dwarfs (France et al. 2013).

In addition to the observational difficulties, predicting stellar UV flux from low-mass stars is also challenging since current models were not designed to calculate emission from the low-density regions of stellar upper atmospheres. As a result, the UV flux received by an exoplanet is often underestimated in photochemical models (Kopparapu et al. 2012; Miguel & Kaltenegger 2014; Tian et al. 2014). Recently, Miguel et al. (2014) demonstrated the significant impact of a star’s Ly$\alpha$ on the photochemistry of the atmospheres of mini-Neptunes at low pressures using the GJ 436 planetary system, one of the few M dwarfs for which Ly$\alpha$ data exist (France et al. 2013).

The total Ly$\alpha$ emission is impossible to measure directly from stars due to scattering of the majority of the photons by the neutral hydrogen of the interstellar medium. Even for the nearest stars it is difficult to directly determine the Ly$\alpha$ flux without using reconstruction techniques applied to high-resolution spectra currently available only with the Hubble Space Telescope’s

* Based on observations made with the NASA Galaxy Evolution Explorer (GALEX). GALEX was operated for NASA by the California Institute of Technology under NASA contract NAS5-98034.
ment further, one also has to take into account Earth’s own geocoronal Lyα emission.

Using reconstructions from Wood et al. (2005) and France et al. (2012, 2013), Linsky et al. (2013) produced correlations of Lyα line fluxes from a sample 46 FGKM stars with other spectral emission lines formed in the chromosphere, which were also observed with either STIS or COS. Although the Mg ii h + k emission lines at 2802.7 and 2795.5 Å also required a correction for interstellar absorption at their cores (Wood et al. 2005; Linsky et al. 2013), they provided the most promising results possibly due to being least affected by metallicity differences. Even with large uncertainties in the Lyα reconstructed fluxes, ≈20% for the FGK stars (Wood et al. 2005) and ≈30% for the M stars (France et al. 2012, 2013), the search for correlations between different activity diagnostics and Lyα is extremely valuable when no other UV spectral data are available.

In view of the severe challenges of measuring or predicting Lyα and Mg ii for many stars, we used the Galaxy Evolution Explorer’s (GALEX) all-sky photometric surveys to search for correlations between FUV and near-ultraviolet (NUV) photometry and the intrinsic Lyα and Mg ii fluxes compiled by Linsky et al. (2013). In the absence of UV spectroscopy, such correlations will allow for estimates of the intrinsic Lyα fluxes from thousands of stars within a few hundred parsecs in the GALEX archive with which to study stellar activity, provide empirical constraints for new cool-star upper-atmosphere models (S. Peacock et al., in preparation) and estimate the incident high-energy radiation affecting the photochemistry and evolution of planetary atmospheres.

2. GALEX NUV AND FUV PHOTOMETRY

The GALEX satellite was launched on 2003 April 28 and observed the UV sky until its mission completion on 2013 June 28. GALEX imaged approximately three-fourths of the sky simultaneously in two UV bands: FUV 1350–1750 Å and NUV 1750–2750 Å, excluding the powerful and complicated Lyα and nominally sensitive to the Mg ii h + k chromospheric lines. The average FWHM of the point-spread functions (PSFs) are 6.5” and 5” in the FUV and NUV, respectively, across a 1:25 field of view. The full description of the instrumental performance is presented by Morrissey et al. (2005). With the failure of the FUV detector in 2009 May, subsequent observations only provided NUV imaging. The fluxes and magnitudes averaged over the entire exposure were produced by the standard GALEX Data Analysis Pipeline (version 4.0) operated at the Caltech Science Operations Center (Morrissey et al. 2007). The current database contains 214,449,551 source measurements (Bianchi 2014) recorded by the All-sky, Medium and Deep Imaging Surveys and many guest investigator programs. The data products are archived at the Barbara A. Mikulski Archive for Space Telescopes.

For this study we used the “aper_7” aperture for the UV photometry, which has a radius of 17’3. This large aperture requires the least aperture correction (0.04 mag in both the in NUV and FUV bandpasses) and accounts for all possible PSFs, even those elongated near the edges of the images. We excluded detections beyond 0.59 from the center of the image to avoid the worst edge effects.

For F and G stars, the flux in the GALEX bandpasses includes a significant fraction of continuum (i.e., photospheric) emission (Figure 1, right; Smith & Redenbaugh 2010) with the remaining flux provided by strong emission lines (C iv, C ii, Si iv, He ii) originating from the stellar upper-atmosphere. K and M stars have FUV and NUV fluxes strongly dominated by these stellar emission lines making GALEX an excellent tool with which to study stellar activity in lower-mass stars (e.g., Robinson et al. 2005; Welsh et al. 2006; Pagano 2009; Findeisen & Hillenbrand 2010; Shkolnik et al. 2011; Rodriguez et al. 2011; Shkolnik 2013).

Twenty-eight of the stars with reconstructed Lyα fluxes compiled by Linsky et al. (2013) were observed by GALEX. These are summarized in Table 1. GALEX observations move...
Kurucz models and applied photospheric fluxes for B8 to K5 stars using the solar-metallicity 

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flux originating solely from upper atmospheric activity. We 

by design, exclude chromospheric emission to isolate the excess 

photospheric emission from stellar atmosphere models, which 

for the given SpT.

distances, and reconstructed Lyα from the Baraffe et al. (1998) models with published stellar ages 

We scaled the fluxes to the stellar surface using radii derived 

with NUV detections and nineteen stars with FUV detections 

Figure 4 of Shkolnik & Barman (2014). This left eight stars 

σ detection threshold and we calculate its 1

the FUV analysis. One M star has an FUV flux below the 

from the literature and 

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Notes.

\(^a\) Data compiled by Linsky et al. (2013).

\(^b\) Stellar radii determined from Baraffe et al. (1998) models using stellar ages and \(T_{\text{eff}}\).

\(^c\) \(T_{\text{eff}}\) from Kraus & Hillenbrand (2007).

into the nonlinear regime after 34 counts s\(^{-1}\) in the FUV and 

108 counts s\(^{-1}\) in the NUV (Morrissey et al. 2007). This required 

us to omit all the bright stars with effective temperatures \(T_{\text{eff}} > 4900\) K from the NUV analysis and one nearby K star from the 

FUV analysis. One M star has an FUV flux below the detection threshold and we calculate its 1\(\sigma\) upper limit using 

Figure 4 of Shkolnik & Barman (2014). This left eight stars 

with NUV detections and nineteen stars with FUV detections 

for analysis.

3. ANALYSIS

Linsky et al. (2013) compiled the spectral types (SpTs), distances, and reconstructed Lyα and Mg ii fluxes scaled to 1 AU 

of 46 stars. Table 1 lists the 28 of these stars observed by \textit{GALEX}. 

We scaled the fluxes to the stellar surface using radii derived from the Baraffe et al. (1998) models with published stellar ages 

from the literature and \(T_{\text{eff}}\) from Kraus & Hillenbrand (2007) 

for the given SpT.

As mentioned above, the \textit{GALEX} bandpasses consist of both photospheric and chromospheric emission. We determined 

photospheric emission from stellar atmosphere models, which 

by design, exclude chromospheric emission to isolate the excess 

flux originating solely from upper atmospheric activity. We 

adopt the semi-empirical results from Findeisen et al. (2011), 

who calculated \textit{GALEX} FUV and NUV magnitudes of the 

photospheric fluxes for B8 to K5 stars using the solar-metallicity 

Kurucz models and applied \(T_{\text{eff}}\) corrections to fit empirical 

color–color plots (see their Table 1 and Figure 5). For stars cooler 

than K5, we use the Phoenix model atmospheres (Hauschildt et al. 1997; Short & Hauschildt 2005) convolved with the 

relevant NUV and FUV normalized transmission curves. (See 

Section 3 of Shkolnik & Barman (2014).) Figure 1 (left) plots the 

surface photospheric flux for our sample as a function of \(T_{\text{eff}}\): 

the Findeisen et al. (2011) fluxes for stars hotter than 4000 K 

and Phoenix model fluxes for cooler stars. The tight correlation 

between the two photospheric flux sources demonstrates their 

consistency.

In both the NUV and FUV detections of our sample, 80\% of the targets have photospheric contributions of <10\% of the 

observed flux. Only one hot star at \(T_{\text{eff}} = 6800\) K appears 

to have nearly no chromospheric emission. Figure 1 (right) plots the ratio of photospheric flux to the observed FUV and 

NUV surface fluxes as a function of \(T_{\text{eff}}\) for our sample. All 

but one of the K and M stars have negligible photospheric 

contributions. The observed and excess NUV and FUV fluxes 

for the sample are listed in Table 1. Although in most cases the 

expected photospheric flux is relatively low, we subtract 

it from the \textit{GALEX} observations such that correlations can 

be made using only upper-atmospheric emission with the Lyα 

and Mg ii chromospheric line (Figure 2). Within uncertainties, 

correlations for the K and M stars are unchanged by this step 

(see Table 2).

We separated the stars into two SpT bins: F and G stars 

and K and M stars for several reasons: (1) the fraction of 

Figure 2. FUV (left column) and NUV (right column) excess surface flux plotted against Lyα (top row) and Mg ii (bottom row) surface flux. Lyα and Mg ii fluxes are taken from Linsky et al. (2013) and scaled to the stellar surface. (A color version of this figure is available in the online journal.)

Table 2

| Regression Fit |
|----------------|
| $\log \left[ F_{\text{FUV,obs}} \right] = A T_{\text{eff}} + B$ |
| $\log \left[ F_{\text{FUV,exc}} \right] = A T_{\text{eff}} + B$ |
| $\log \left[ F_{\text{Lyα}} \right] = A \log \left[ F_{\text{NUV,exc}} \right] + B$ |
| $\log \left[ F_{\text{Lyα}} \right] = A \log \left[ F_{\text{FUV,exc}} \right] + B$ |
| $\log \left[ F_{\text{Mg ii}} \right] = A \log \left[ F_{\text{NUV,exc}} \right] + B$ |
| $\log \left[ F_{\text{Mg ii}} \right] = A \log \left[ F_{\text{FUV,exc}} \right] + B$ |
| $\log \left[ F_{\text{Lyα}} / F_{\text{NUV,exc}} \right] = A \log \left[ F_{\text{NUV,exc}} \right] + B$ |
| $\log \left[ F_{\text{Lyα}} / F_{\text{FUV,exc}} \right] = A \log \left[ F_{\text{FUV,exc}} \right] + B$ |
| $\log \left[ F_{\text{Mg ii}} / F_{\text{NUV,exc}} \right] = A \log \left[ F_{\text{NUV,exc}} \right] + B$ |
| $\log \left[ F_{\text{Mg ii}} / F_{\text{FUV,exc}} \right] = A \log \left[ F_{\text{FUV,exc}} \right] + B$ |

| SpT Range | A | B | R |
|-----------|---|---|---|
| F5 V−M5.5 V | 28 | 1.519E−03 ± 4.080E−05 | −0.6094 ± 0.2063 | 0.99 |
| F5 V−M5.5 V | 28 | 2.640E−03 ± 6.484E−05 | −10.6934 ± 0.3279 | 0.99 |
| K2 V−M5.5 V | 8 | 0.430 ± 0.094 | 3.595 ± 0.575 | 0.88 |
| K2 V−M5.5 V | 8 | 0.447 ± 0.069 | 3.549 ± 0.409 | 0.94 |
| K0 V−M5.5 V | 10 | 0.432 ± 0.068 | 3.969 ± 0.359 | 0.91 |
| K0 V−M5.5 V | 8 | 0.853 ± 0.427 | 1.325 ± 2.307 | 0.63 |
| K2 V−M5.5 V | 8 | −5.56 ± 0.069 | 3.570 ± 0.411 | −0.96 |
| K2 V−M5.5 V | 8 | −5.70 ± 0.071 | 3.970 ± 0.374 | −0.94 |
| F5 V−G9 V | 8 | 0.853 ± 0.427 | 1.325 ± 2.307 | 0.63 |
| K2 V−M5.5 V | 8 | 0.872 ± 0.049 | 3.349 ± 0.301 | 0.99 |
| K0 V−M5.5 V | 10 | 0.916 ± 0.116 | 1.272 ± 0.610 | 0.94 |
| F5 V−G9 V | 6 | 1.056 ± 0.177 | 0.599 ± 0.946 | 0.95 |

Note. Surface flux units are in erg cm$^{-2}$ s$^{-1}$.

the photosphere in the hotter stars is much higher than in the cooler stars for which it is effectively negligible. Thus, any uncertainties in the models used will not disrupt the results for the K and M stars, as it might for the hotter stars. (2) Low-mass stars tend to have higher flare activity levels, so the non-contemporaneous data sets used in this study may induce added scatter for K and M stars.  

6 HST observations of the old M dwarf GJ 876 (~3 Gyr; Correia et al. 2010) show flaring in upper atmospheric emission lines with flux levels increasing by at least a factor of 10 during a 5800 s observation (France et al. 2012).
with a strong correlation of for the Lyα fluxes and the Mg ii lines they studied, Mg ii doublet, the strongest emission feature probing lower emission temperatures. However, with the few data points for F and G stars, their small flux distribution, and uncertainties in the model fluxes, these correlations should be applied cautiously.

For the sample of K and M stars where the photospheric model fluxes are negligible, we find that the Lyα surface fluxes correlate well with both the FUV and NUV excess surface fluxes such that 

\[ \log \left[ \frac{F_{\lambda,\text{exc}}}{F_{\nu,\text{exc}}} \right] = (0.43 \pm 0.07) * \log \left[ \frac{F_{\lambda,\text{exc}}}{F_{\nu,\text{exc}}} \right] + (3.97 \pm 0.36) \] 

and

\[ \log \left[ \frac{F_{\lambda,\text{exc}}}{F_{\nu,\text{exc}}} \right] = (0.45 \pm 0.07) * \log \left[ \frac{F_{\lambda,\text{exc}}}{F_{\nu,\text{exc}}} \right] + (3.55 \pm 0.41) \] 

For stars too bright in the NUV, the FUV correlation can be used, and for more distant stars where the FUV is not detected, the Mg ii lines providing another window into a strong stellar chromospheric emission feature probing lower emission temperatures.

With good correlations in both GALEX bandpasses, estimates of intrinsic Lyα and Mg ii can now be made for thousands of K and M stars out to a few hundred parsecs from Earth. These data will constrain a new and much needed suite of model chromospheres, as well as provide planetary atmosphere models with more realistic Lyα and Mg ii values without the need for high-resolution UV spectroscopy.

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2007; Scalo et al. 2007; Heller & Armstrong 2014), a separate correlation for these stars is appropriate for providing Lyα and Mg ii flux estimates with which to study planetary atmospheres. Figure 2 (left) shows the FUV excess to Lyα surface flux correlation for the 11 K and M stars with a correlation coefficient \( R = 0.91 \), excluding the one upper limit. The F and G correlation has eight stars with a weaker correlation coefficient \( R = 0.63 \) and low statistical significance. Figure 2 (right) shows the correlation for the Lyα surface flux against the NUV excess surface flux with a strong correlation of \( R = 0.94 \) for eight K and M stars.7 Due to the brightness of the F and G stars, no NUV observations were reliable due to the nonlinearity of the GALEX data.

Linsky et al. (2013) pointed out that of all the emission lines they studied, Mg ii may provide the most accurate Lyα predictions as metallicity effects appear the smallest. Our analysis also exhibits highly significant correlations between GALEX fluxes and the Mg ii lines for the K and M stars (Figure 2, bottom). Figure 3 shows the ratio of Lyα to the GALEX flux as a function of FUV and NUV flux. These correlations reveal how the relative strength of the Lyα compared to the broadband fluxes weakens as the FUV and NUV excess flux increases. All of the regression fits to the correlations are summarized in Table 2.

4. SUMMARY

Lyα is the strongest stellar UV emission line and provides the most important source of radiative losses in a star’s upper chromosphere and lower transition region. As such, it may also be the greatest source of molecular photodissociation in the atmosphere of an orbiting exoplanet. Measuring a star’s intrinsic Lyα flux requires space-based high-resolution FUV spectroscopy plus intricate reconstruction techniques to correct for interstellar absorption and geocoronal emission. In order to gain access to the Lyα emission of many more stars than is currently possible to observe (i.e., with HST), we sought to find correlations between literature values of reconstructed Lyα emission and broadband stellar upper atmospheric emission measured from GALEX FUV and NUV photometry.

Our sample consisted of the 28 stars which have both reconstructed Lyα and GALEX observations ranging in SpT from F5 to M5.5. We separated our sample into 11 F and G stars and 17 K and M stars as the photospheric contribution to the GALEX bandpasses, stellar variability, and chromospheric temperature structure (e.g., Walkowicz & Hawley 2009) differ in the two groups. The F and G stars were limited to only eight FUV observations as they were too bright for reliable NUV measurements. There is a weak correlation between the FUV excess flux and Lyα, and a strong one between GALEX/FUV and the Mg ii doublet, the strongest emission feature in the NUV spectral region. However, with the few data points for F and G stars, their small flux distribution, and uncertainties in the model fluxes, these correlations should be applied cautiously.

For the sample of K and M stars where the photospheric model fluxes are negligible, we find that the Lyα surface fluxes correlate well with both the FUV and NUV excess surface fluxes such that

\[ \log \left[ \frac{F_{\lambda,\text{exc}}}{F_{\nu,\text{exc}}} \right] = (0.43 \pm 0.07) * \log \left[ \frac{F_{\lambda,\text{exc}}}{F_{\nu,\text{exc}}} \right] + (3.97 \pm 0.36) \] 

and

\[ \log \left[ \frac{F_{\lambda,\text{exc}}}{F_{\nu,\text{exc}}} \right] = (0.45 \pm 0.07) * \log \left[ \frac{F_{\lambda,\text{exc}}}{F_{\nu,\text{exc}}} \right] + (3.55 \pm 0.41) \] 

For stars too bright in the NUV, the FUV correlation can be used, and for more distant stars where the FUV is not detected, the NUV correlation can be used. Additionally, the GALEX excess fluxes for K and M stars correlate well with the Mg ii lines providing another window into a strong stellar chromospheric emission feature probing lower emission temperatures.

With good correlations in both GALEX bandpasses, estimates of intrinsic Lyα and Mg ii can now be made for thousands of K and M stars out to a few hundred parsecs from Earth. These data will constrain a new and much needed suite of model chromospheres, as well as provide planetary atmosphere models with more realistic Lyα and Mg ii values without the need for high-resolution UV spectroscopy.

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7 Note that the strongest UV emitting M star in the sample is the young Speedy Mic (40 Myr; Kraus et al. 2014) and the weakest emitting is the old GJ 876. Claire et al. (2012) have shown that stellar high-energy flux decreases with age for a sample of Sun-like stars with steepening decline at shorter wavelengths. The same is true for M dwarfs (Preibisch & Feigelson 2005; Shkolnik & Barman 2014).
made use of the VizieR catalog, SIMBAD database, the Mikulski Archive for Space Telescopes (MAST), and the Phoenix and Kurucz photosphere-only atmospheric models. This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France (Ochsenbein et al. 2000) and the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts.

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