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Solar and Stellar Flares and their Effects on Planets
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Ultraviolet and X-ray Irradiance and Flares from Low-Mass Exoplanet Host Stars

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Abstract. The spectral and temporal behavior of exoplanet host stars is a critical input to models of the chemistry and evolution of planetary atmospheres. High-energy photons (X-ray to NUV) from these stars regulate the atmospheric temperature profiles and photochemistry on orbiting planets, influencing the production of potential "biomarker" gases. We report first results from the MUSCLES Treasury Survey, a study of time-resolved UV and X-ray spectroscopy of nearby M and K dwarf exoplanet host stars. This program uses contemporaneous Hubble Space Telescope and Chandra (or XMM) observations to characterize the time variability of the energetic radiation field incident on the habitable zones planetary systems at d $\lesssim$ 20 pc. We find that all exoplanet host stars observed to date exhibit significant levels of chromospheric and transition region UV emission. M dwarf exoplanet host stars display 30 – 7000% UV emission line amplitude variations on timescales of minutes-to-hours. The relative flare/quiescent UV flux amplitudes on weakly active planet-hosting M dwarfs are comparable to active flare stars (e.g., AD Leo), despite their weak optical activity indices (e.g., Ca II H and K equivalent widths). We also detect similar UV flare behavior on a subset of our K dwarf exoplanet host stars. We conclude that strong flares and stochastic variability are common, even on "optically inactive" M dwarfs hosting planetary systems. These results argue that the traditional assumption of weak UV fields and low flare rates on older low-mass stars needs to be revised.

Keywords. Low-mass stars, ultraviolet flares, X-ray flares, exoplanet atmospheres

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1. Introduction

M dwarf planetary systems present a truly exciting opportunity to discover the first habitable extrasolar planets in the next 5 – 10 years. Their low ratio of stellar-to-planetary mass allows detection of lower mass planets using the primary detection techniques (radial velocity and transits). Moreover, the habitable zone (HZ) around a star, where liquid water may exist on terrestrial planet surfaces, moves inward with decreasing stellar luminosity. These factors make habitable planets easier to detect around M dwarfs.

The formation and maintenance of an Earth-like atmosphere depends on the incident stellar spectrum in complex ways. The ultraviolet (UV) stellar spectrum in particular drives/regulates upper atmosphere chemistry on Earth-like planets. M and K dwarfs show significantly larger variability and fraction of their emitted bolometric luminosity at UV wavelengths than solar-type stars, yet their actual spectral and temporal behavior is not well studied except for a few young (< 1 Gyr), active flare stars. At present, we cannot accurately predict the UV spectrum of a particular M dwarf without a direct observation. Without the stellar UV spectrum, we cannot accurately model the spectra of Earth-like planets in these systems, a necessary prerequisite for characterizing these

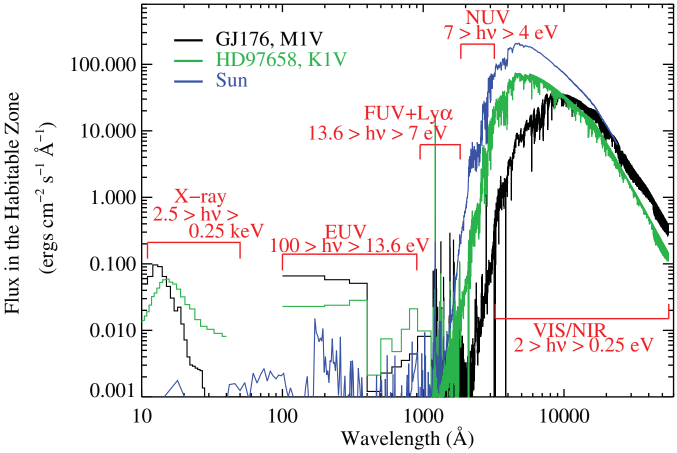

Figure 1. Panchromatic SEDs, scaled to the effective 1 AU habitable zone distance, for planet-hosting G (Sun, G2V), K (HD 97658, K1V), and M (GJ 176, M2.5V) dwarfs. The NUV and optical fluxes are larger for the G dwarf, while the FUV fluxes are comparable and the lower–mass stars have higher EUV and X-ray fluxes than the Sun. The solar spectra are taken from Woods *et al.* (2009) and the M and K dwarf spectra are from MUSCLES.

objects. The paucity of UV spectra of low-mass stars is thereby currently limiting our ability to reliably predict possible atmospheric biomarkers.

An important measurement relating to the habitability of extrasolar planets is the time variability of the energetic incident radiation. While most of the quiescent UV emission from M dwarfs comes from emission lines, continuum emission becomes the dominant UV luminosity source during flares (Kowalski *et al.* 2010). The relative UV line emission line strengths also vary during flares (e.g., Loyd & France 2014 and references therein). Thus, molecular species in the atmospheres of HZ planets will be “selectively pumped” during quiescent periods; only species that have spectral coincidences with stellar emission lines will be subject to large energy input from the host star. However, during strong continuum flares, the relative excitation and dissociation rates could change radically. Therefore spectrally resolved observations are essential for understanding the impact of time variability on HZ planetary atmospheres. The amplitude and duration of flare activity on older M-star exoplanetary hosts is completely unexplored, although GALEX near-UV imaging observations suggests that flares may significantly alter the steady-state chemistry in the atmospheres of planets in the HZ (Welsh *et al.* 2006).

We have carried out a large panchromatic observing program to measure the spectrally and temporally resolved UV radiation fields in nearby M and K dwarf exoplanet host stars. This program is the MUSCLES (Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems) Treasury Survey, an X-ray/UV/optical coordinated observing program managed as part of an HST Cycle 22 treasury guest observing program (PI – K. France). In this proceeding, we present preliminary time-variability results from the program, examining extraordinary flare observations that were acquired in the portion of the survey that was complete prior to the Solar and Stellar Flare Symposium (August 2015). We refer the reader to the conference proceeding of R. O. Parke Loyd (Loyd *et al.* 2015; this volume) for more details on the UV flare quantification presented herein. The full survey will be complete in September 2015; first refereed journal papers on the MUSCLES Treasury Survey are in preparation and are anticipated for late 2015.

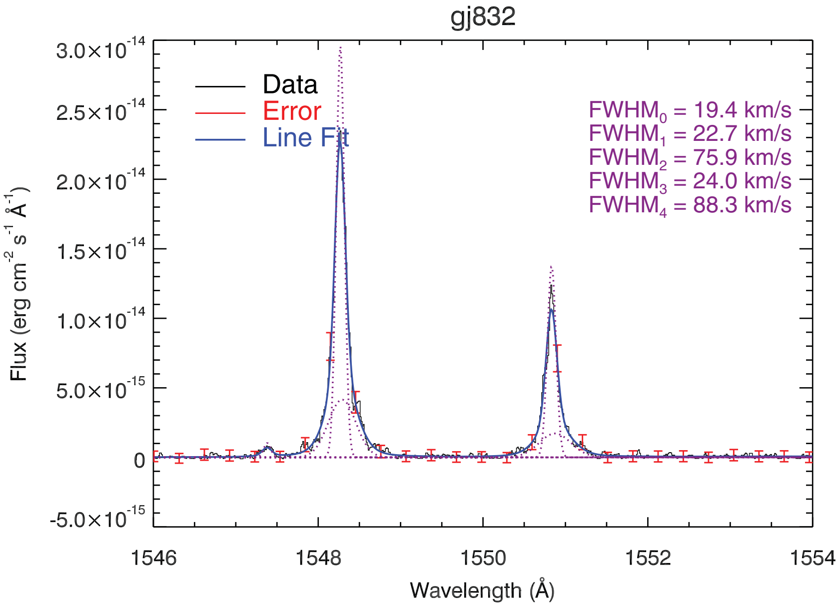

Figure 2. C IV line profiles from GJ 832, observed with COS G160M as part of MUSCLES. Gaussian FWHMs are shown for each component at upper right. The narrow (19 km s^{-1}) component is an H_2 emission line pumped by strong Lyα radiation (France *et al.* 2012, 2013).

2. Overview and Spectral Energy Distributions

The MUSCLES Treasury Survey represents the first treasury X-ray → UV → optical spectral database of planet-hosting low-mass stars, essential to the characterization of their potentially habitable planets. We use STIS G140M and E140M observations of Lyα and models of the local interstellar hydrogen abundance to reconstruct the intrinsic Lyα profiles incident upon planets in the habitable zone. Lyα reconstruction is critical, because even for nearby stars, the interstellar medium removes more than 80% of the intrinsic stellar line flux from our line-of-sight. Our profile reconstruction technique has been vetted against previous estimates of cool star Lyα fluxes (e.g., Wood *et al.* 2005), producing robust Lyα intensities (France *et al.* 2013).

We use COS G130M and G160M observations to catalog the FUV metal emission lines and to simultaneously create time-resolved profiles of lines tracing activity in different layers of the stellar atmosphere (e.g., C II vs. N V). COS/STIS G230L and E230M observations provide near-UV spectra. STIS G430L spectra are observationally inexpensive and provide an essential connection with ground-based observations and stellar photosphere models. X-ray observations are made by Chandra or XMM for most sources, scheduled as close in time as feasible and simultaneous for several targets. The X-ray luminosities provide a direct measure of the coronal properties of the host stars, a critical input for the heating of the planetary atmospheres. An example of the panchromatic SEDs are shown in Figure 1 for representative G, K, and M dwarf exoplanet host stars.

The 15 targets (Table 1) include 7 M dwarfs and 4 K dwarfs hosting planetary systems. The M dwarfs span a range of spectral types (from M1 – M6), high (GJ 176) to low (GJ 581) X-ray luminosity fraction (an indicator of activity level), and planetary systems ranging from Jupiters (GJ 832) to super-Neptunes (GJ 436) to super-Earths (GJ 1214). ∼65 % of the exoplanet host stars in our sample (7/11) harbor Super-Earths (M_{plan} < 10 $M_{\oplus}$). The 4 M dwarfs without known exoplanets provide a control sample

Table 1. MUSCLES Treasury Survey – Target List

Star	Distance (pc)	Type	Exoplanet Mass $M \sin i$ (M_{Jup})	Semi-major Axis (AU)	*HST* T_{exp} (orbits)	X-ray Mode	X-ray T_{exp} (ks)
GJ 1214	13.0	M6	**0.020**	0.0143	15	*CXO*-GO15	[30]
GJ 876	4.7	M4	1.935, 0.61, **0.018**, 0.039	0.208, 0.130, 0.0208, 0.0208	10	*Chandra*	20 + 10
GJ 581	6.3	M3	0.050, **0.017**, **0.019**, **0.006**	0.041, 0.073, 0.218, 0.029	11	*CXO*-GO15	[50]
GJ 436	10.3	M2.5	0.073	0.0287	13	*Chandra*	20 + 10
GJ 176	9.4	M2.5	**0.026**	0.066	14	*Chandra*	20 + 10
GJ 667C	6.9	M1.5	**0.018**, **0.014**	0.049,0.123	11	*Chandra*	20 + 10
GJ 832	4.9	M1	0.64	3.4	10	*XMM*	10
HD 85512	11.2	K6	**0.011**	0.26	8	*CXO*-GO	[40]
HD 40307	12.9	K2.5	**0.013**, **0.021**, 0.030, **0.011**, **0.016**, **0.022**	0.047, 0.080, 0.132, 0.189, 0.247, 0.600	8	*CXO*-GO	[50]
ϵ Eri	3.2	K2	1.1 – 1.55	3.4	8	*XMM*	10
HD 97658	21.1	K1	**0.020**	0.080	9	*CXO*-GO	[50]
GJ 1061	3.7	M5	...	...	2		
GJ 628	4.3	M4	...	...	2		
HD 173739	3.6	M3	...	...	2		
GJ 887	3.3	M2	...	...	2		

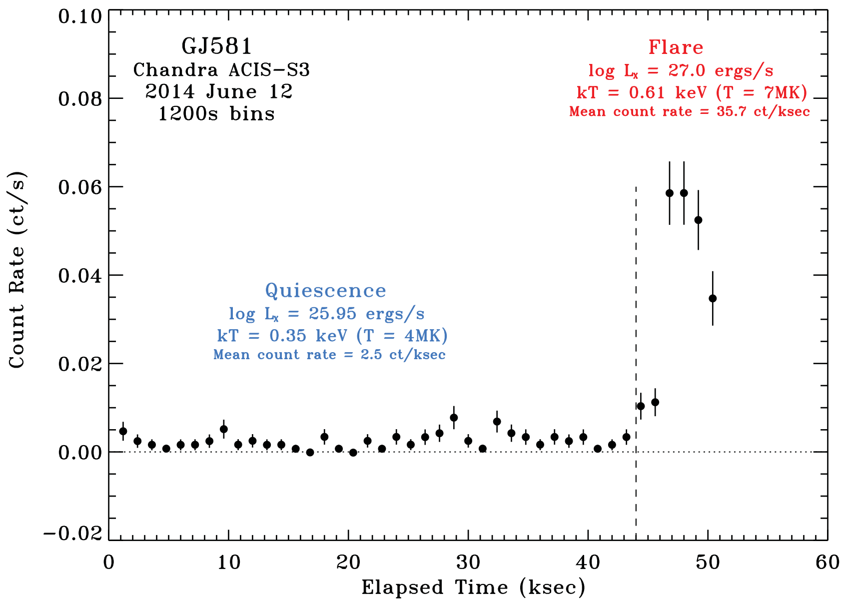

Figure 3. Strong X-ray flare detected on GJ 581 (Chandra) during MUSCLES observations.

for high energy emission from chromospheric (e.g., Si II, Al II) and transition region (e.g., C IV) tracers. Example C IV spectra from the M1 dwarf GJ 832 are shown in Figure 2. These spectra are best fitted with two emission components, narrow component and a broad redshifted component suggesting microflaring events in the upper stellar atmosphere traced by $\sim 10^5$ K gas (Wood *et al.* 1997).

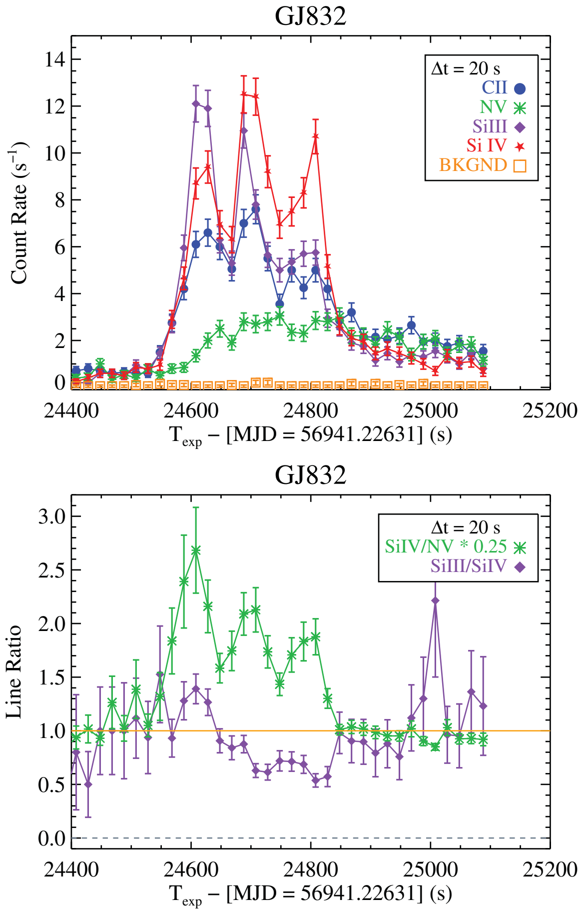

Figure 4. HST-COS lightcurves from a strong UV flare on GJ 832. Spectral variability is seen within the flare.

3. First X-ray and UV Flare Results

In this proceeding, we present two representative examples of the types of flare behavior we are seeing from the MUSCLES survey stars: a strong X-ray flare and a strong UV flare. Bear in mind that these sources all have Ca II K equivalent widths less than 1 Å, classifying them as "weakly active" or "optically inactive" stars (Walkowicz & Hawley 2009). For comparison, traditional M dwarf flare stars have Ca II K equivalent widths in the range 5 – 10 Å. There was some expectation that these stars might not maintain detectable basal levels of UV and X-ray emission, and it was not expected that they would show the frequent, energetic flares found on their more active cousins.

Figure 3 shows an impulsive X-ray flare on the optically quiet M3 dwarf GJ 581. GJ 581 was not detected in the ROSAT survey presented by Poppenhaeger *et al.* (2010), suggesting a very low level of X-ray activity. Our June 2014 Chandra observations confirmed the low stellar X-ray flux observed by Swift (Vitale & France 2013) for the first 40 ks of observing. The X-ray luminosity was measured at $\log_{10}(L_X) = 25.9$ with a coronal temperature of approximately 4×10^6 K. Approximately 43 ks into the observation a large coronal flare occured, increasing the X-ray luminosity by an order of magnitude, $\log_{10}(L_X) = 27.0$, and increasing the coronal temperature fit by almost a factor of two, 7×10^6 K.

Figure 4 shows an impulsive ultraviolet flare on the optically quiet M1 dwarf GJ 832. This data was recorded in time-tag mode with HST-COS using the G130M grating during one of the dedicated flare monitoring visits (5 contiguous spacecraft orbits). The light curves (top panel) of various metal emission lines tracing the upper chromospheric and transition region are shown at a 20 second cadence. These lines sample formation temperatures roughly spanning 2×10^4 K (C II) – 2×10^5 K (N V). GJ 832 maintained a low, but non-zero, basal UV flux level for the first $\sim$ 24 ks of observing before going into a strong flare event starting at 24.5 ks. The flare/quiescent emission line flux increases were of order 50 for the brightest lines (Si III 1206 and Si IV 1394, 1403), rivaling the largest relative UV flux increases ever detected on classical flare stars like AD Leo (Hawley *et al.* 1991; Hawley *et al.* 2003). The bottom panel shows line ratios for Si IV/N V and Si III/Si IV, showing significant spectral variability in the flare as a function of time, presumably driven by the thermal evolution of the post-reconnection plasma.

Publically available SEDs High-level data products will be delivered to MAST as a resource for the exoplanet modeling community as well as stellar astrophysicists, who will be able to take advantage of the first uniform UV data set for the study of "weakly active" M dwarfs that includes reliable measurements of Lyα and resolved stellar emission lines.

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