Chapter 8. Mechanisms of flaring and CME activity on the Sun and stars

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Solar and Stellar Magnetic Fields: Origins and Manifestations
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The UV/X-ray radiation fields and particle (CME) flows of M dwarf exoplanet host stars

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Abstract. The high energy X-ray and UV radiation fields of host stars play a crucial role in determining the atmospheric conditions and habitability of potentially-habitable exoplanets. This paper focuses on the major surveys of the UV/X-ray emissions of M- and K-type exoplanet hosts that have been undertaken by the MUSCLES and MegaMUSCLES Hubble Space Telescope (HST) Treasury programs and associated contemporaneous X-ray and ground-based observations. The quiescent and flaring radiation (both photons and implied particles) were observed from this extensive sample of relatively old, low mass, exoplanet host stars and show that, from the viewpoint of a habitable-zone exoplanet, there is no such thing as an "inactive" M dwarf star. The resulting implications are significant for planetary habitability. Extensive monitoring of the X-ray/UV emission from a representative younger M dwarf is also presented and the direct stellar effects that influence exoplanets during the earlier phases of their formation and evolution discussed.

Keywords. stars: late-type, stars: activity, stars: flare, planetary systems, X-rays: stars, ultraviolet: stars

1. Introduction to M Dwarfs and their Exoplanets

Low mass M and late-K dwarf stars are currently the focus of major research efforts to discover and study their exoplanet systems. Discovering planets orbiting such low mass stars is far easier than for solar-like stars using both transit and radial velocity techniques, because the effects of the planets on the stellar signal is far larger. Additionally, studies have shown the earth-like or super-earth planets are commoner around M dwarfs and large gas-giant planets are rarer than for higher mass stars. M dwarfs show very strong surface magnetic fields (see e.g. Shulyak *et al.* (2019)). These complex 3-6 kG magnetic fields fill and control the outer atmospheres of all M dwarfs (Afram & Berdyugina (2019)) and lead to bright, variable coronal X-ray and chromospheric/transition-region ultraviolet emission.

<u>*Habitable zones*</u>.

The concept of habitable zones is fundamental to discussions of whether life, particularly as we know it on Earth, would be possible on exoplanets. The zeroth order definition of habitability is to consider whether an exoplanet orbits its host star at a distance that provides an equilibrium temperature compatible with the presence of liquid water on its surface. Beyond this initial starting point, there are many complicating factors including the properties of the planet's atmosphere and magnetic field. An excellent discussion of habitability is provided by Shields, Ballard & Johnson (2016).

M dwarfs are far less luminous than the Sun and consequently their liquid water habitable zones must be much closer to the star. While the habitable zone for an early-G dwarf lies between 0.8 and 2 AU from the star, the same region for an M dwarf is at

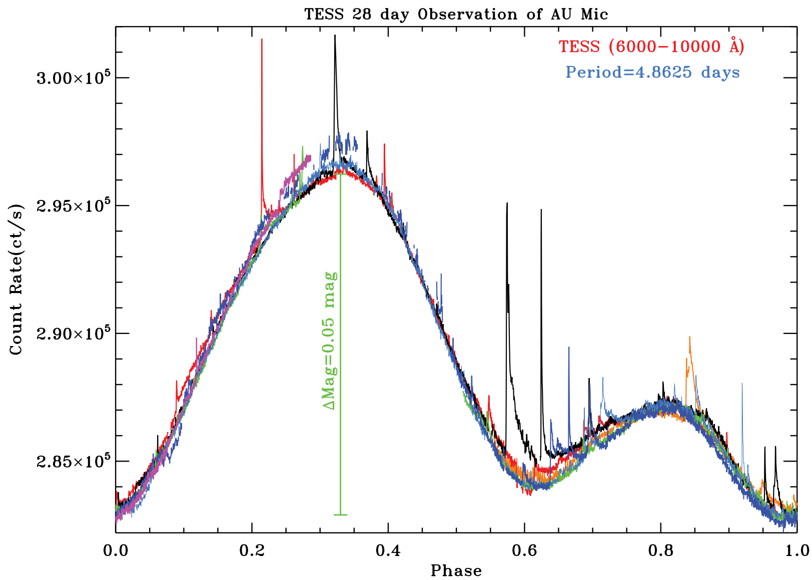

Figure 1. Broadband optical TESS light-curve of AU Mic phase-folded using a 4.8625 day rotational period. Clear starspot rotational modulation with a 5% full amplitude is the dominant repetitive variability (See Wisniewski *et al.* (2019)).

radii between 0.1 and 0.2 AU. Flares on M dwarfs are at least as strong as solar flares, so they can have a far greater effect on their habitable zones planets, than solar flares on the Earth.

Role of different spectral regions.

Stellar radiation in different spectral regions affects an exoplanet in different ways. The optical/IR radiation is the majority of the radiated energy and controls the atmospheric and surface heating of the planet. X-ray and EUV ($\leq$ 912 Å) radiation plays a major role in thermospheric heating and atmospheric erosion. The intermediate FUV/NUV radiation controls the atmospheric chemistry via molecular formation and photolysis. The FUV radiation is dominated by the 1215.67 Å H I Lyman-α emission line (Youngblood *et al.* (2016)). The EUV region contains a mixture of coronal and transition region emission lines that must be reconstructed using spectral information recorded in the X-ray and FUV regions.

2. Young Active M Dwarfs: Conditions Encountered by Newly-formed Exoplanets

Example: The young star AU Mic. The intense stellar activity shown by young M dwarfs is well illustrated by recent observations of the dMe star AU Mic. AU Mic is a relatively massive M0 V star with a well established age of 24$\pm$3 Myr, based on its membership in the Beta Pictoris Moving Group (Bell, Mamajek & Naylor (2015)). It has an edge-on dust debris disk indicative of the presence of a protoplanetary system (Kalas *et al.* (2004), Wisniewski *et al.* (2019)), which is known to contain at least two exoplanets based on transit measurements.

The presence of optical flaring on AU Mic is obvious in a 28 day TESS observation obtained between 2018 Jul 25 - Aug 22. Even though the sensitivity of TESS lies in the red part of the optical spectral region (6000-10000 Å) where flaring is far harder to detect than in the blue, many flare enhancements are clearly detected in the rotational-phase-folded light-curve (Fig. 1) .

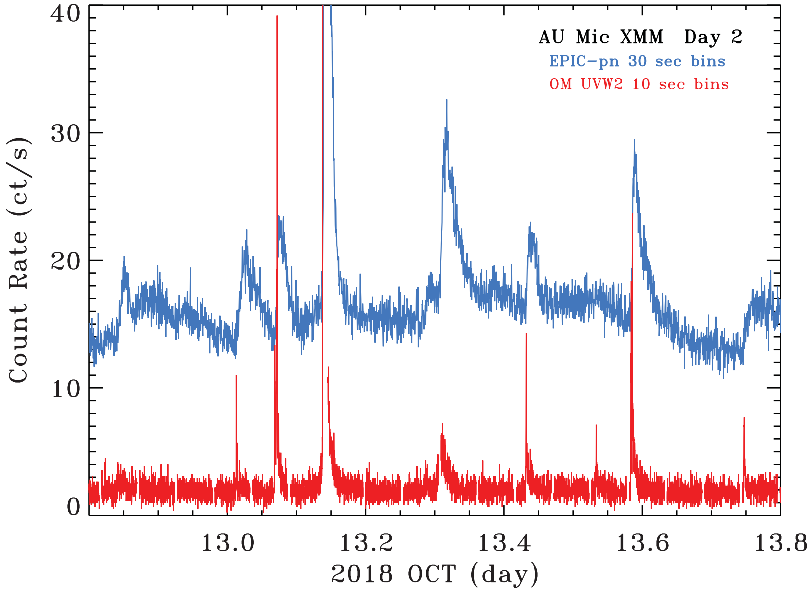

Figure 2. One day of XMM-Newton flaring variability from a 550 kilosecond observation of AU Mic. The upper curve (blue) shows the EPIC-pn soft-X-ray variability and the lower curve (red) shows the OM UVW2 NUV variability. The X-ray flares show exponential rise and decay time-scales roughly 10 times longer than those seen for the NUV flares. The NUV emission is produced during the impulsive phase of the flare when high energy particles are being accelerated into the stellar surface, while the soft X-rays are emitted during the gradual phase when the heated coronal plasma is cooling. Clearly, the planets orbiting AU Mic are impacted by multiple flare events on a daily basis.

The major flares produced by magnetic energy release are revealed in even more detail by a 7 day XMM-Newton Large Project (PI Adam Kowalski). Soft X-ray and near-ultraviolet emission were monitored for a total time of 550 kiloseconds. In Fig. 2 the EPIC-pn (soft X-ray) and OM UVW2 (NUV) variability observed during a 1 day time interval are presented. These data were obtained 11 stellar rotations after the TESS data shown in Fig. 1. On average ∼4 flares were detected per day with 19 flares detected in both X-rays and NUV, and a further 8 X-ray flares seen when the OM was not working. The largest flare had an X-ray energy of 10^{33} ergs and 21 flares had X-ray energies $\geq 10^{32}$ ergs.

AU Mic is capable of producing even more extreme flares than those seen in our XMM observation. In 1992 during the commissioning phase of the EUVE satellite an almost 4 day observation of AU Mic contained a very large flare outburst that lasted 2 days (Cully *et al.* (1993)). The EUVE Deep Survey (DS) detector sampled coronal emission in the 65-190 Å spectral region and the DS light-curve peaked at a luminosity of 10^{30} ergs s^{-1}. The total flare energy in the DS bandpass was 3×10^{34} ergs. Based on the temperature evolution derived for this flare by Monsignori Fossi *et al.* (1996)) and Katsova, Drake, & Livshits (1999)), the corresponding soft X-ray (0.3-10 keV) energy would have been $\sim 2 \times 10^{35}$ ergs and thus a factor of 100 larger than the largest flare seen in the 2018 XMM-Newton observation. Such large flare events are likely to cause severe atmospheric erosion from close-in exoplanets and may well be responsible for large-scale structures that are observed moving outwards in the AU Mic disk (Boccaletti *et al.* (2018), Wisniewski *et al.* (2019)).

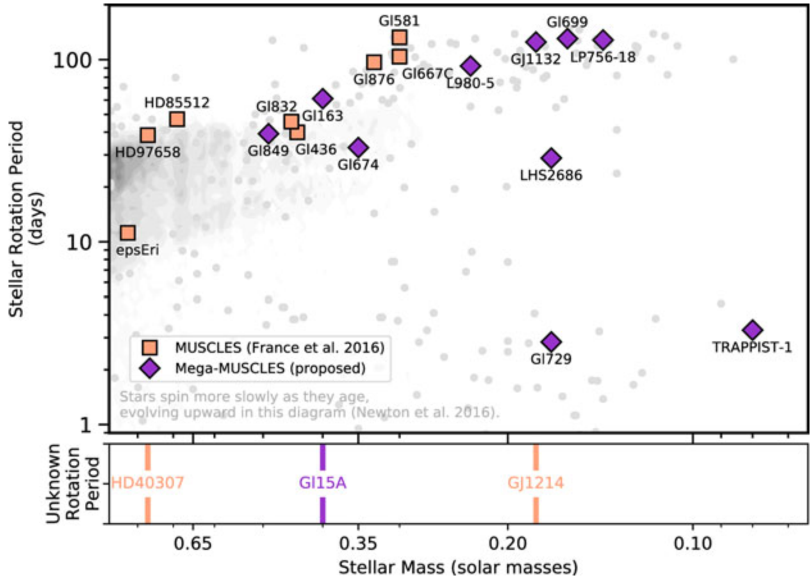

Figure 3. MUSCLES/MegaMUSCLES sample of K/M dwarfs as a function of stellar mass and rotation period. These stars are all exoplanet hosts, typically with super-Earth planets within or near to their habitable zones. These stars provide an as-yet unique sampling of stellar magnetic activity on low-activity, low mass stars. (Observed targets GJ176, GJ649, and GJ676A are not shown on this plot.)

3. MUSCLES/MegaMUSCLES: Exploring Conditions Around Mature M Dwarfs

While considerable efforts have been devoted to studying young active M dwarfs in the ultraviolet and X-ray regions, until recently comparatively little was known about the activity levels of older "inactive" M dwarfs.

M dwarf sample. The MUSCLES (125 orbits) and MegaMUSCLES (157 orbits) HST Treasury programs have conducted an in-depth study of the UV and X-ray spectral energy distributions of K and M dwarf exoplanet host stars with a range of rotation periods and activity levels. A sample of 24 stars with spectral types from K1 to M8 have been studied with HST UV observations and supporting X-ray observations from Chandra and XMM-Newton (see Fig. 3). The stars range from still fast-rotating (few day period) stars to older stars with ∼100 day rotation periods. Specific aims include characterizing the energetic radiation environment in the stars' habitable zones, measure the flare distributions on these less active stars, and providing basic observational inputs to modeling the atmospheric photochemistry and the production of molecular tracers.

Panchromatic spectral energy distributions (SEDs). A fundamental product of the MUSCLES/MegaMUSCLES programs are SEDs that cover the complete wavelength range from the infrared through the optical and ultraviolet to the X-ray region (Loyd *et al.* (2016)). These SEDs provide vital input to the modeling of exoplanets and their atmospheres. All the results from the MUSCLES project and growing datasets from MegaMUSCLES are available at https://archive.stsci.edu/prepds/muscles/.

FUV/NUV balance and atmospheric chemistry. The balance between the FUV (912-1700 Å) and NUV (1700-3200 Å) radiation has a strong influence on oxygen chemistry of Earth-like habitable zone exoplanets and the abundances of molecular oxygen and ozone. The FUV/NUV ratio increases from 10^{-3} for a Sun-like star to 10^{-2} by early-K spectral type and reaches 0.2-0.7 for M dwarfs. This increase in FUV dominance can lead

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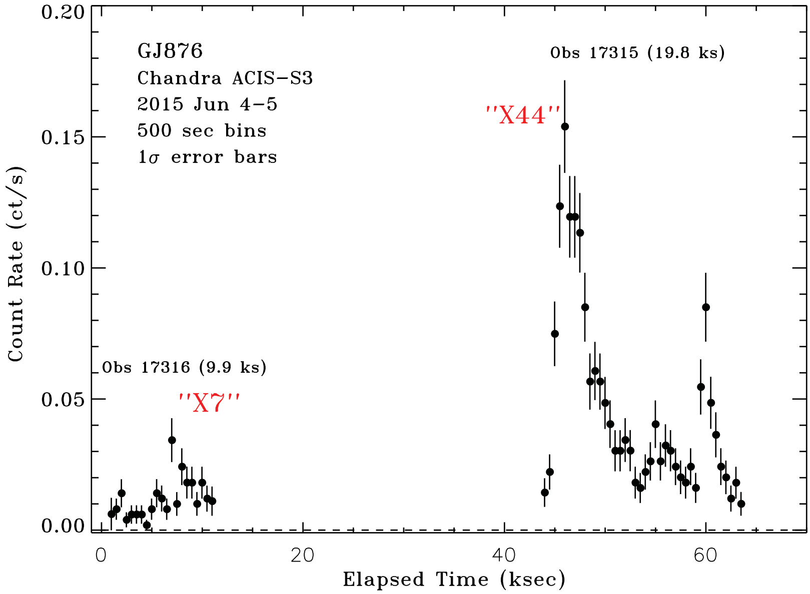

Figure 4. Chandra ACIS-S soft X-ray light-curve of the slowly rotating M5 dwarf GJ876. The flare in the 1st observation is equivalent to an X7 solar flare in the star's habitable zone, while the large flare in the 2nd observation is equivalent to an X44 flare. For comparison, on the Sun an X10 flare occurs once every few years, while the largest known solar flare, the Carrington Flare of 1859, is thought to have been an X45 event.

to the production of significant O_2 and O_3 without the involvement of biotic processes and the false interpretation of the presence of such molecules as biosignatures.

Flares: UV and X-ray variability. Perhaps the most important result from the MUSCLES and MegaMUSCLES surveys is the discovery that strong UV/X-ray flare activity is present on all M dwarfs even down to the oldest, slowly rotating and lowest mass stars sampled. (Wilson *et al.* (2019)). FUV and X-ray flares were observed that reached peaks at 10-100 times the quiescent emission on timescales of 10^2-10^3 seconds. These observations were enabled by the temporal variability studies possible using the Cosmic Origins Spectrograph (COS) on HST (Green *et al.* (2012)) and the photon counting X-ray imagers on Chandra and XMM-Newton. COS provides both flare-related flux and spectral line profile monitoring. Loyd *et al.* (2018) studied the FUV variability seen in the COS data for the MUSCLES sample and found that most of the nominally "inactive" stars showed significant flaring in transition region and chromospheric emission lines. While the FUV emission declines as M dwarfs age and rotate more slowly, the level of flaring emission relative to quiescent emission remains constant.

Almost all the stars observed show X-ray variability, often in the form of large flare outbursts and at other times as clear changes in quiescent flux between observations at different times. Several examples are described by Youngblood *et al.* (2017), including the multiple flares seen by Chandra from the slowly-rotating (P_{rot} = 97 days) M4 dwarf GJ876 (see Fig. 4). These flares when viewed from the habitable zone are remarkable in comparison to present day solar flares that impact the Earth.

Flares: CMEs and energetic particles. Exoplanets are vulnerable not only to the high energy radiation generated by stellar flares but also any energetic particles within coronal mass ejections (CMEs) released as part of the flare magnetic reconnection process. However, it is difficult to estimate the particle flux associated with a particular flare. This is particularly difficult because the observed flare properties indicate flare processes and

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conditions that appear to be beyond those seen in solar flares. For example, COS spectra of a flare on the intermediate rotation (P_{rot} = 33 days) M2.5 star GJ674 showed an unexpected blue FUV continuum below 1200 Å with a color temperature of ∼40,000 K, which requires a far denser emitting flare footpoint than provided by existing radiative hydrodynamic flare models (Froning *et al.* (2019)). One approach is to extrapolate from solar flares and CMEs to try to estimate the potential particle flux. Youngblood *et al.* (2017) used correlations between solar flare soft X-rays and CME fluxes and stellar X-ray and He II 1640 Å fluxes to derive rough estimates of M dwarf CME proton fluxes. These estimates indicate that severe atmospheric changes would result. However, the magnetic fields of M dwarfs are far stronger than on the Sun and it will likely be far harder for a CME to break loose from the star (see Gome (2020)). Even with a cutoff of CME release for flares with lower energies, there are still very many large flares occurring on both younger and older M dwarfs that, even if only a small number have associated CMEs, dramatic effects on exoplanet atmospheres are almost inevitable.

4. Conclusions

High energy X-ray and UV radiation has a significant influence on exoplanets orbiting M dwarf stars. This radiation is extremely intense during the early phases of protoplanetary system evolution, but, while it declines with stellar age and is weaker with decreasing stellar mass, it continues to be important for all M dwarfs throughout their lives. The X-ray/UV radiation is inherently variable and produces exoplanetary illumination that requires time-dependent modeling to adequately study exoplanet atmospheres. While still a matter of debate, any coronal mass ejections associated with the frequent large flares will have severe effects on the exoplanet atmospheres. Despite the significant high energy radiation from M dwarf host stars, it is still unclear how its effects would influence the presence of life on an exoplanet. Obvious mitigating factors include the role of surface water in absorbing high energy photons and how the presence of strong planetary magnetic fields might shield the surface from high energy particles.

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Discussion

Luhmann: How well do we know the interplanetary conditions around M dwarf stars? Are they similar to those of the Solar System?

Brown: We know far less about the interplanetary conditions around M dwarfs than around the Sun. Detailed modeling of the magnetic field structure has been performed for a variety of young M dwarfs, which typically shows stronger and more complex field geometry than seen on the Sun. Far less is known about the conditions around older, less active, M dwarfs.

Luhmann: Extreme SEP events in our solar system do not necessarily scale with indicators, such as flare X-rays, because they modify the shocks that are producing them. Thus, care needs to be taken with scaling relationships.

Brown: Indeed, it is unclear how to extrapolate solar relationships to the far more active M dwarf situation. However, provided that large M dwarf flares are related to plasma release above some critical energy, the CME-related particle release will almost inevitably lead to important effects in the atmospheres of habitable-zone exoplanets.

Strassmeier: Could the interplanetary material flip the FUV/NUV ratio again when measured at a distance similar to Jupiter's?

Brown: Detailed studies of the circumstellar environments of M dwarfs show almost no gas and only a little dust present, even for the evolutionary stage represented by stars like AU Mic, so the FUV/NUV ratio should not be changed from the exoplanet's perspective.