Magnetic Activity and Flares in the Near-UV of Exoplanet Host Stars

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Overview

- Overview of M dwarfs
- Flares from magnetically active M dwarfs (dMe stars)
- NUV flare properties: what's known and not known
- What new simulations with electron beam heating predict
M dwarf (dM) Stars

-- $1/3 \, R_{\text{Sun}}$
-- $1/3 \, M_{\text{Sun}}$
-- $T_{\text{eff}} \approx 2200-3800 \, \text{K}$
-- $L < 1/100 \, L_{\text{Sun}}$
-- Habitable zone: $0.05-0.1 \, \text{au}$
-- fully convective at $M4$
-- 70% of stars
-- $P_{\text{rot}} < 3$ days
-- $d_{\text{Me}} \Rightarrow$ H-alpha emission in quiescence (“active”)
-- rate of $10^{32}$ erg flares $\approx 1-2$ / day

Johns-Krull & Valenti 1996
Saar & Linsky 1985

-- very strong photospheric magnetic fields: 4 kG, 50% of surface

SDSS u-band
We observe red dwarf stars for flares for a similar reason that we observe them for planets.

3.6m NTT at La Silla Observatory
Magnetic activity saturation in M dwarfs

\[ \frac{L_x}{L_{\text{bol}}} \]

\[ R_o = \frac{P_{\text{rot}}}{\tau} \] (Rossby #)

Wright & Drake 2016 Nature
Active M dwarf (dMe) Stars

Long activity lifetimes (according to H-alpha)

Late type (M5-M8) dwarfs stay active also for long rotation periods
Flares Rates of Active vs. "Inactive" M dwarfs

Flare rate varies among active stars, from active to inactive

Average flaring luminosity in U increases with non-flaring stellar luminosity

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Osten et al. 2012

SUN? (Kretzschmar 2011) - SOHO/VIRGO TSI

Osten et al. 2012

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Swift BAT Triggered on Large Stellar X-Ray Flare

- DG CVn is a pair of M4 V stars at ~18 pc, believed to be very young ~ 30 Myr.
- DG CVn flared on April 23, 2014.

- Record "super-flare" for solar neighborhood M dwarf star.
- Peak V-band increase 200x; X-ray super bolometric luminosity.
- Peak X-ray temperature of 300 MK is ~ 10 x solar flare $T_{\text{peak}}$.
- Total flare energy $10^{36}$ erg is $10^3$ x largest solar flare energy.
- Flare decay time is 2-3 weeks.

Is Prox Cen b habitable?

- $5 \times 10^{29}$ erg (total) vs. $5 \times 10^{30}$ erg (total) for Sun
- Can occasionally produce $10^{32}$ erg flares (Gudel et al. 2002)
- Inverse square law for habitable zone: 400x irradiance
Overview

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Basic Facts of Giant NUV Flares

  - 45% of 120 - 820 nm energy in NUV from 200 - 400 nm
  - like a $T \sim 9000 - 10^4$ K blackbody
  - 90% energy in flare continuum (Hawley & Pettersen 1991), but can vary (Hawley et al. 2007, Kowalski et al. 2013)
Flare irradiation of planetary atmospheres

- Ionization of D region (X-rays)
  - Thomson et al. 2005

- Ozone photodissociation (NUV)
  - Banks & Kockarts 1973, *Aeronomy*
  - Ackerman 1971

- EUV and Lyman-alpha also very important (Milligan et al. 2014)
Solar Flares

• white-light: broadband (optical & NUV) impulsive radiation coincident in time and space with (nonthermal) X-rays (E > 20 keV)

Observations of limb solar flares (Martinez-Oliveros et al. 2012, Krucker et al. 2015)

• white-light: spatially confined to "footpoints"

• soft (thermal) x-rays: hot loops
A Two-Ribbon Solar Flare

SDO/AIA (171A, T~800,000 K)

Movie showing lower corona (from above)
The solar-stellar connection

Impulsive phase (U-band is white-light, proxy for hard X-rays), 10,000 K “footpoints”

Gradual phase (bright soft X-rays), 10-30 MK “loops”

Gudel et al. 2002 (flare on dM5.5e Proxima Centauri)
The Near-UV in Quiescence

Hawley & Pettersen 1991
NUV/Blue Flare Spectra at Balmer jump

How we compare to models:

- Measure the **Balmer jump ratio** $= \frac{F_{3600}}{F_{4170}}$
- Measure a blue-to-red continuum ratio $= \frac{F_{4170}}{F_{6000}}$

M dwarf flare spectra; Kowalski et al. 2013
Balmer jump ratio time evolution

ULTRACAM light curves of flares on YZ CMi

Kowalski et al. 2016
Larger Balmer jump ratio

Bluer (hotter) optical continuum

- Models calculated with the 1D RADYN flare code (Carlsson & Stein 1997, Allred et al. 2015)

$F# = \text{energy flux density}$

Kowalski et al. 2016
Heated chromosphere to 5-10 MK

Thermal pressure spikes (shocks)

Electron beams

Initial transition region evaporation

Chromospheric evaporation

Chromospheric condensation (CC)

$\log m_{\text{ref}}$

$T_{\text{ref}} \approx 10^4 \text{K}$

Stationary flare layers: $T \leq T_{\text{ref}}$

Photosphere

Figure not to scale
High electron beam energy flux densities create compressions in the chromosphere, can reproduce continuum and line radiation.
Where do the flare continuum spectra peak in the NUV?

Kowalski & Allred 2018

Hawley & Pettersen 1991
Conclusions

- Exoplanet hosts (dM and dMe stars) produce energetic continuum and line radiation during flares in the NUV.
- The properties can be reproduced by high-energy flux density electron beams.
- Need NUV data of impulsive phase from 200 - 350 nm to understand the origin of this radiation in dM and dMe flares and for comprehensive input to ozone photochemistry models.