X-ray variability of cool stars: Magnetic activity and accretion

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Variability related to magnetic activity

**flares**
- hours – days
- radio – X-rays

**rotating cool spot**
- days – weeks
- opt., IR, X-rays(?)

**dynamo cycles**
- years
- opt. emiss. lines + photom, X-rays

**geometric effects**
- days – weeks
- opt., IR, X-rays(?)

**intrinsic**
- years
- opt., IR, X-rays(?)

Variability related to accretion, disks + outflows
Variability related to magnetic activity

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Changing visibility of active regions due to rotation

Energy release in magnetic reconnection events

Varying surface coverage with active regions
Simultaneous optical/X-ray flare with XMM-Newton on an UCD

Fast optical event: $\Delta V \sim 6$ mag in 40 sec

$\Delta t_{opt/X-ray}$ peak < 20 sec

Standard flare scenario predicts optical flare preceding X-ray flare because chromosphere is heated directly by accelerated electrons, and corona lights up in X-rays after evaporation of chromosphere.

Stelzer et al. (2006)
Flare dynamics

**Simultaneous optical/X-ray flare with XMM-Newton on an UCD**

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**XMM-Newton potential:**
Joint X-ray/optical flare lightcurves at high time-resolution w. EPIC + Optical Monitor

- Identify benchmark targets for Athena
  - Athena studies rise phase of flares:
    1. mass motions
       $\Delta v \sim 100$ km/s for $\lambda/\Delta\lambda \sim 3000$;
    2. flare loop length

**Pye et al. (2015):**
"X-ray flares in XMM-Newton serendipitous catalog"
Magnetic structure (flare loops)

In the presence of sustained heating, the observed flare decay is longer than $\tau_{th}$; the difference is related to the slope $\zeta$ in the $T$ – EM diagram:

$$\frac{\tau_{lc}}{\tau_{th}} = F(\zeta).$$

Instrument dependent calibration “F”.

The loop length is:

$$L = \frac{\tau_{th}\sqrt{T_{pk}}}{3.7 \times 10^{-4}}$$

Reale et al. (1997, 2007)
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Getman et al. (2008)

Reale et al. (1997, 2007)
Magnetic structure (flare loops)

**Bright X-ray flares associated with large loops (L > Rₜ)**

→ star-disk loops? (Favata et al. 2005)

Mostly seen on disk-less YSOs (Aarnio et al. 2010)

→ large loops only in absence of disks?

**XMM-Newton potential:**

X-ray loop studies of stars with well-known YSO status (Spitzer! WISE!)

Alternative loop length estimate

from wavelet analysis of XMM-Newton oscillations

Lopez-Santiago et al. (2016)

**XMM-Newton potential:**

Test new analysis methods

Getman et al. (2008)
Magnetic structure (flare loops)

Star-disk X-ray flare triggers accretion event in MHD simulations (Orlando et al. 2011)

Not yet observed!
→ XMM-Newton + opt. monitoring (1-2d)

Testing new scientific scenario = significant observing time investment!
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Brightness modulation by rotating cool star spots (magn. field footpoints)

**X-rays**
- (Corona; 1-10 MK)

**White Light**
- (Photosphere; 6000 K)

Coronal structures coincident with photospheric star spots → rotational modulation in X-rays expected

Stelzer et al. (2003)

V410 Tau
Simultaneous optical + X-ray monitoring:
Rotation + flare variability

16 XMM-Newton observations in Kepler field
(Pizzocaro et al., in prep.)

- 131 stars joint with Kepler/XMM
- typ. XMM exposure: 50 ksec
  (typ. $P_{\text{rot}} \sim 1...50$ d)

poster Pizzocaro et al.
(stellar parameters + rotation-activity relation)
Simultaneous optical + X-ray monitoring: Rotation + flare variability

16 XMM-Newton observations in Kepler field (Pizzocaro et al., in prep.)

Simultaneous opt/X-ray flares
Simultaneous optical + X-ray monitoring: Rotation + flare variability

Simultaneous opt/X-ray flares

Search for X-ray rot.modulation
Synergies with space- and ground-based photometric monitoring

Prepare for simultaneous X-ray / optical monitoring with upcoming space photometry missions of bright stars

TESS:
Need flexible scheduling for long uninterrupted observations

<table>
<thead>
<tr>
<th>MISSION</th>
<th>Operation</th>
<th>Target brightness (V)</th>
<th>Length of lightcurves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler</td>
<td>2009 - 2013</td>
<td>12 – 16 mag</td>
<td>4 yrs</td>
</tr>
<tr>
<td>K2</td>
<td>2014 - 2017</td>
<td>&gt; 4 mag (&gt; 11)</td>
<td>~80 d</td>
</tr>
<tr>
<td>TESS</td>
<td>2017 - 2018</td>
<td>8 – 12 mag</td>
<td>27+ d</td>
</tr>
<tr>
<td>LSST</td>
<td>2022 - 2032</td>
<td>&gt; 16 mag</td>
<td>10 yrs (200pts)</td>
</tr>
<tr>
<td>PLATO</td>
<td>2024 - 2027</td>
<td>4 – 11 mag</td>
<td>2 – 3 yrs</td>
</tr>
</tbody>
</table>
Variability related to magnetic activity

- flares: hours – days, radio – X-rays
- rotating cool spot: days – weeks, opt., IR, X-rays(?)
- dynamo cycles: years, opt.emiss.lines+photom, X-rays

Sanz-Forcada et al. 2013
**Variability related to magnetic activity**

**Yohkoh:**
Solar 11-yr X-ray cycle

- **dynamo cycles**
  - years
  - opt.emiss.lines+photom, X-rays

- Why study activity cycles?
  - *clue to stellar dynamo mechanism*
  - *influence on planet atmospheres*

- Only 4 X-ray cycles known to date.

- Orlando et al. (2002)
- Sanz-Forcada et al. 2013
Stellar X-ray cycles

- **Yohkoh:**
  - Solar 11-yr X-ray cycle
  - Sun: $\Delta L_X \sim 1.7$ dex

- **XMM-Newton:**
  - Decade-long baseline needed to cover long cycles

- **61 Cyg AB:**
  - K5V + K7V (resolved in X-rays)
  - Ca II H+K cycles of 7.3 yrs + 11.7 yrs
  - $\Delta L_X \sim 0.5$ dex

- **HD 81809, G2IV:**
  - 8yr Ca II H+K cycle
  - $\Delta L_X \sim 0.5$ dex

- **Poster Robrade et al.**

- **Favata et al. (2008)**
  - Flare?
Stellar X-ray cycles

Iota Hor:
* 1 of 4 known X-ray cycles;
* shortest cycle: 1.6 yrs;
* youngest star with cycle (500Myr)

XMM-Newton in the next decade:
* cycle-to-cycle variations of short cycles;
* double cycle?
* eROSITA cycles → XMM spectroscopy

(X-ray) cycle on young star differs from older star
→ X-ray irradiation of planets changes in long timescales
Stellar X-ray + magnetic cycles

Structure of corona inferred from ZDI magnetic map:

- predicted rotational modulation of X-rays
- predicted cycle modulation of X-rays

(see e.g. Alvarado-Gomez et al. 2016)

(X-ray) cycle on young star differs from older star
→ X-ray irradiation of planets changes in long timescales

**XMM-Newton in the next decade:**
- sample coordination with magn. field studies

**ZDI magnetic map**
Alvarado-Gomez et al., in prep.
Age (long-term) evolution of X-ray activity

* high-energy emission drops by 3 dex from 10 Myr to Gyrs

* age decay faster at shorter $\lambda$

β_{X} \sim -1.1
β_{FUV} \sim -0.9
β_{NUV} \sim -0.7

Stelzer et al. (2013)
See also Shkolnik & Barman (2014)

XMM-Newton + Chandra:
Use WD in resolved WD / M binaries as chronometer for age of M dwarf
“Calibrating the time-evolution of the high-energy emission of GKM stars”

Extension of ‘The Sun in time’ to M stars with WD companions

Prelim. Result: Evolution of X-rays in M dwarfs unclear!
(large dispersion for given age)

XMM-Newton:
high sensitivity for faint stars; build up samples!

Also: X-rays from stars with asteroseismic ages (Booth & Poppenhäuser, in prep.)
Discovering stars among XMMSL transients

Slew transients:
• \( \geq 6 \) counts in soft band
• count rate \( \geq 70 \) times ROSAT
\( \rightarrow 119 \) sources (March 2014)

* search for counterpart / photometry:
  2MASS, WISE, Swift, GALEX, SDSS, Hipp, Tycho2, UCAC4, PPMXL, NVSS
* optical follow-up spectroscopy
\( \rightarrow \) identify stars \( \rightarrow \) study space distribution

Systematic exploitation of the XMM-slew
\( \rightarrow \) Stellar population studies
(Gaia parallaxes a huge leap!)

Courtesy J. Lopez-Santiago
Synergies with other facilities increasingly important:

- Gaia distances (will be publicly accessible)
- simultaneous X-ray / optical monitoring (needs to be organized)
- opt. spectropolarimetry (needs careful sample selection)
The Benz-Guedel relation is violated by UCDs (first noted by Berger et al. 2002)

UCDs with bright radio emission show radio bursts
  → Electron Cyclotron Maser
  (Hallinan et al. 2006; 2008)
  but no or very weak X-rays

UCDs without detectable radio emission
  but with X-ray flares

Ultracool dwarf (UCD) = object with SpT equal or later M7; either star or brown dwarf

Stelzer et al. (2012)
Ultracool dwarf radio/X-ray connection

Scenario from Stelzer et al. (2012)

Slow rotation:
X-ray flaring, no radio

Fast rotation:
Radio bursts, no X-rays

Possible origin of dichotomy:
(A) Rotation
(B) Magnetic field structure

Suggestion by Williams et al. (2013)
strong field ?
weak field ?

New Territory in UCD radio emission:

EMU
Evolutionary Map of the Universe

2016+

Magnetic field maps of UCDs:
• 2018+: SPIRou/CFHT, CRIRES+/VLT

Photom. rotation periods of UCDs:
• monitoring at 4m+ telescopes

Multi-λ support for XMM-Newton observations of UCDs mandatory!
Variable phenomena of accretion, disks + outflows

- geometric effects
  - days – weeks
  - opt., IR, X-rays (?)

- intrinsic
  - years
  - opt., IR, X-rays (?)

- occultation by accretion column or by disk warp
- rotating hot (accretion) spot

- variable accretion rate (FUOr, EXOr outbursts)
- disk FeKα emission excited by star
Variable phenomena of accretion, disks + outflows

- occultation by accretion column or by disk warp
- rotating hot (accretion) spot

**Low** \( L_x \) for stars with disk

- geometric effects
  - days – weeks
  - opt., IR

**Intrinsic**
- variable accretion rate (FUOr, EXOr outbursts)
- disk FeK\(\alpha\) emission excited by star

- opt., IR, X-rays(?)

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Gregory et al. (2007)

Hartmann (2008)
Variable X-rays in accretion bursts?

Evolving two-temperature X-ray plasma during optical accretion outburst: soft component (accretion) decreasing

Long-term (months – years) X-ray monitoring possibly with the same instrument → revisit observed EXOrs in the next decade

EX Lup
Prototype EXOr variable (accretion outbursts on months timescale)
6.4keV (Fe Kα) emission from pre-MS stars

Very strong 6.4keV line \((W \sim 1400 \text{ eV})\) for short time during flare rise

fluorescence calculations underpredict observed Kα flux;
partial obscuration of continuum X-ray source that contributes to Kα flux
(Drake et al. 2007)

V1486 Ori (COUP #331)

500 ks XMM-Newton in \(\rho\) Oph Core F; 4 papers published

Results from DROXO (Stelzer et al. 2010):
Time-resolved spectroscopy yields higher Fe Kα equivalent widths than time-averaged spectroscopy
(see also Giardino et al. 2007)
X-ray variability of late-type stars: potential for

Results from DROXO (Pizzocaro et al. 2015):
X-ray transient emission in three 1ksec time-slots from a Class I protostar

other similar cases identified.....

500 ks XMM-Newton in ρ Oph Core F; 4 papers published

poster Pizzocaro et al.
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- **geometric effects**
  - days – weeks
  - opt., IR

* systematic search (EXTraS pipeline !)
  → identify benchmarks for Athena
* Novel analysis (wavelets)

Simultan. monitoring with photometric space missions

Decade-long monitoring (cycle-to-cycle variations, multiple cycles)

Decade-long monitoring (FUOr, EXOr outbursts)

Origin of the Fe Kα emission (flare vs quiescent)

Intrinsic
  - years
  - opt., IR, X-rays(?)

Variable phenomena of accretion, disks + outflows

SYNERGIES

SAMPLE

COMPLETENESS