HIGH ENERGY STELLAR AND (EXO) PLANETARY SCIENCE IN THE NEXT DECADE AND BEYOND

Scott Wolk (SAO/CfA)
• Xarm – μcal spectral resolution, poor angular resolution.
• Arcus – Dispersive grating resolution at low energies.
• AXIS – excellent angular resolution, large effective area, Si detectors
• Strobe – X/TAP – high count rate X-ray missions
• Athena – Better μcal spectral resolution, good angular resolution.
• Lynx – Even better μcal spectral resolution, better grating resolution and excellent angular resolution and area.
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What will we be able to measure?

- Crisp X-ray images with ability to separate sources and study diffuse emission
- Spatially resolved spectroscopy of point and diffuse emission
- Temporally resolve emission
- Good quality grating spectra with ability to measure key line diagnostics
Imaging Spectroscopy

µcalorimeters:
IFU spectra of extended objects such as PN, Comets, diffuse emission & planets

Branduardi-Raymont et al. (2007)
μcalorimeters:
IFU spectra of extended objects such as PN, Comets, diffuse emission
Studies of Nearby Star Formation Regions

- Cluster Census
- Transition disk timescales
- X-ray effects on cluster morphology

PSF is directly related to the reach of the telescope
Studies of Nearby Star Formation Regions

Chandra 0.5” PSF
~Lynx

XMM-Newton 4.4” PSF
~Athena (5” PSF)
Overwhelming datasets

Chandra 0.5” PSF
~Lynx
Studies of Nearby Star Formation Regions

Well done with μcal imaging spectroscopy

- Cluster Census
- Transition disk timescales
- X-ray effects on cluster morphology
- Detecting grain evolution
- X-rays from protostars
- Effect of X-rays on forming planets disks
  - Especially flares.
- Understanding the magnetic fields.
- What are the statistics of radio flaring for young stellar objects?
- Are radio flares correlated with X-ray flares?
- Understanding diffuse emission and feedback.
- What is the relationship between X-rays and radio emission from YSOs?
Issues in Stellar Coronae

- Magnetic field generation via dynamo
  - Does the activity/rotation relation hold for low mass stars?
- Coronal heating and radiation
- Evolution of magnetic activity
  - Angular momentum loss in accreting stars
  - Accretion shocks
- Flares and coronal mass ejections (CMEs)
- Stellar wind drivers

This requires: Dispersive Gratings

*Chandra* and XMM-Newton grating spectroscopy only available for a few dozen (active) stars.
Coronal Spectroscopy

Resolving each line enables investigations of coronal dynamics, broadening mechanisms.

Testing coronal heating models using temperature-sensitive dielectronic recombination (DR) lines.

A 5ks *Arcus* observation will identify these lines; longer observations capture the changes in the dynamic coronal environment.
Coronal Spectroscopy

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Chung et al. (2004) excess broadening of Algol interpreted as rotational broadening from a radially extended corona.
Coronal and Accretion Dynamics

Resolving each line enables investigations of temperatures, densities, coronal dynamics, broadening mechanisms.

TW Hya is one of the deepest, highest resolution X-ray spectra of a young star ever taken:

- X-ray spectra of young stars show more than accretion plus magnetic activity.
- X-rays implicated in rapid heating of protoplanetary disks.
- After stars lose their disks, X-ray surveys are the only way to find young stellar objects.
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Smith et al. (2009)
Coronal and Accretion Dynamics

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Potential Exoplanet Applications

Where do planets form? Where do they migrate?

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Brickhouse et al. (2010)

The impact of a high quality X-ray spectra: need more than accretion source + coronal source to explain all the myriad diagnostics (electron density, electron temperature, absorbing column)
µcalorimeters vs. & Gratings

You need both

-- Gratings don’t image µcal issues
-- continuum placement for measurement of triplet lines
-- blending lines

Arcus/Lynx have dispersive gratings
-- better quality than Chandra in ~10/1 ks in Taurus-Auriga objects, ~100/10 ks at Orion
Future Stellar Studies

- Searching for habitability
- Focused on low mass M dwarfs
- Habitable zones are closer to star
- Issues include destruction of atmosphere by:
  - Stellar flares and concurrent CME’s
    - AD Leo can recover from massive flare/proton flux (Segura+ 2010)
  - Stellar UV to X-ray radiation
    - But UV is promising for catalyzing prebiotic chemistry (Ranjan & Sasselov 2016)
  - Stellar winds (Garaffo+ 2017; Wargelin & Drake 2002)
    - But planet’s B field may channel particles only to polar regions (Driscoll+ 2013)
What is Exoplanet Science?

Not just this

radial velocity — velocity shift of a star due to star+planet

astrometry — seeing the reflex motion of the star due to star+planet system

direct imaging — block out the light of the star to see the planet directly

transit — decrease in stellar light

microlensing — gravitational lensing due to star+planet system passing in front of a background star
What is Exoplanet Science?

“Blue of the sky” measures total amount of atmosphere

“Vegetation jump” indicates presence of land plants

Carbon dioxide suggests possible volcanic activity

Methane indicates presence of anaerobic bacteria

Oxygen and ozone were produced by living organisms

Water vapor suggests habitability

But also this
What is Exoplanet Science?

And this

And this
What is Exoplanet Science?

The star’s magnetic field creates an ecosystem which helps to set the environment that planets (and life) experience (Lingam & Loeb 2018). Stellar magnetospheres influence the inner edge of the traditional habitable zone (Garaffo et al. 2016, 2017).
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*High energy processes & protoplanetary disks*

- **Flare X-rays**
- **Flare MeV particles**
- **Mag field lines**
- **Cosmic rays**
- **Dead zone**
- **Proto-Jupiter**
- **Proto-Earth**
- **Ionized MHD turbulent zone**

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*Slide courtesy of Eric Feigelson*
Potential Exoplanet Applications

How does the coronal emission of stars affect exoplanets?

- Stellar twins are not magnetic twins; star’s X-ray emission at early ages is a much larger factor in planetary irradiation
- Planetary atmospheric evolution is fundamentally linked to XEUV emission
- X-rays trace magnetic structure directly

Johnstone et al. (2015)
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![Graph showing X-ray and EUV emission spectra](image)
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<table>
<thead>
<tr>
<th>Spectral class</th>
<th>GI 65A</th>
<th>GI 65B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>0.1225 M☉</td>
<td>0.1195 M☉</td>
</tr>
<tr>
<td>Radius</td>
<td>0.165 R☉</td>
<td>0.159 R☉</td>
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<tr>
<td>Rot. vsini</td>
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<td>30.6 km/s</td>
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<tr>
<td>Rot. period</td>
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<td>5.45 hr</td>
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<tr>
<td>Metall. [Fe/H]</td>
<td>-0.03</td>
<td>-0.12</td>
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<tr>
<td>&lt;Bf&gt; Stokes I</td>
<td>5.2 kG</td>
<td>6.7 kG</td>
</tr>
<tr>
<td>B₀rift strength</td>
<td>0.3 kG</td>
<td>1.3 kG</td>
</tr>
</tbody>
</table>

- complex, non-axisymmetric
- axisymmetric dipole

Potential Exoplanet Applications

How do the characteristics of flares change with time and what impact does this have on exoplanet conditions?

- Systematic change of $T_{\text{max}}$, $E_{\text{flare}}$, $L_{x,\text{max}}$ on flares of stars with varying mass, age, magnetic configuration as input to evolution of planetary irradiation
- Influence of energetic particles inferred from line profiles

Large flare on Proxima
Güdel et al. (2002)

- Blueshifts in solar flares up to several hundred km/s, coincide with start of nonthermal hard X-ray emission from accelerated particles (Antonucci et al. 1990)
- Peak in nonthermal line broadening occurs at same time as maximum amount of hard X-ray emission (Antonucci et al. 1982)
2D wavelet analysis of 2012 light curve
Description: A damped magneto acoustic oscillation in the flaring loop.

\[ \Delta I/I \sim 4 \pi n k_B T/B^2 \]

\[ T \sim 12 \text{ MK} \]
\[ n: \text{density} = 5 \times 10^{10} \text{ cm}^{-3} \]
\[ \text{(from RGS data)} \]

\[ B \rightarrow 40-100 \text{ G} \]

\[ \tau \sim L/c_s \]
\[ c_s = \sim T^{0.5} \]
\[ \tau = \text{oscillation period} \sim 4 \text{ ks} \]
\[ L=\text{Const.} \times \tau_{osc} NT^{0.5} \]
\[ L \sim 5 \text{ R}_* \]

Pillitteri et al. (2014)
Implication of the wavelet analysis
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A UV flare only has a 1% effect on the depletion of the ozone layer of an Earth-like planet in the habitable zone of an M dwarf

A UV flare + proton event (>10 MeV) inferred from scaling from solar events, results in complete destruction of the ozone layer in the atmosphere of an Earth-like planet in the habitable zone of an M dwarf

Segura et al. (2010)
How do stellar winds change with time and what impact does this have on exoplanet conditions?

- Stellar wind mass loss critical to atmospheric escape process
- Detect charge exchange emission from nearest ~20 stars to constrain $\dot{M}$
- Coronal mass ejections play an important role in potential habitability; need a way to constrain them

Future capabilities give several ways to detect CMEs:
1. Changes in column density during a flare
2. Detection of coronal dimming
3. Velocity signatures in the line profile
- An active K1V at 19 pc ($L_x \sim 10L_{\odot}$)
- Age estimated at 0.6 Gyr
  - Based on rotation period and
  - X-ray activity
- Hot Jupiter in a 2.2 day orbit
- Wide M4 Companion (very inactive)

Poppenhaeger, Schmitt & Wolk (2013)
Measuring Exoplanet Atmospheres

How does the size of the exoplanet’s atmosphere contribute to its mass loss?

- Planetary $\dot{M}$ depends on $F_{\text{XEUV}}$
- Larger estimated mass loss than if the planetary atmosphere is not extended
- Direct measures of atmospheric height

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Poppenhaeger et al. (2013) for the hot Jupiter HD 189733b
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The observatories of the next decade and a half will represent a major leap forward in X-ray capabilities.

These missions will address questions relevant to furthering our understanding the energetic side of stellar ecosystems, constraining the impact of stellar activity on extrasolar planets and habitability:

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Donati & Landstreet (2009) extrapolation from photospheric magnetic field

Cohen et al. (2017) dynamo simulation
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Densities

Need ability to resolve lines from nearby blends, underlying continuum
Densities enable constraints on length scales, dynamics

![Graph showing UX Ari: OVII f/i=const with plots for different f/i values](image1)

![Graph showing log(n_e/cm^-3) vs. f/i for various stars](image2)
Accretion

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Accretion shocks
What will we be able to measure?

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X-RAY LINE RATIO DIAGNOSTICS
FOR DENSITY AND TEMPERATURE

\[ N_e = 6 \times 10^{12} \text{ cm}^{-3} \]
\[ 3 \times 10^{12} \]
\[ 6 \times 10^{11} \]

\[ \text{Mg XI} \]
\[ \text{Ne IX} \]
\[ \text{O VII} \]

\[ T_e = 2.50 \pm 0.25 \text{ MK} \]

This looks like the accretion shock!
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Wood et al. (2004) indirect measures of stellar mass loss

Credit: NASA MAVEN mission
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Wargelin & Drake (2001)
Upper limit on mass loss rate of Proxima from charge-exchange emission from interaction of stellar wind with ISM
Requires spatial resolution <0.5” to resolve CX from central point source
Applicable to ~20 nearby stars.