Astro2020 Science White Paper
Stellar X-ray Spectroscopy Addresses Fundamental Physics of Stellar Coronae, Accretion, and Winds, and Informs Stellar and Planetary Studies

Thematic Areas: ☑ Planetary Systems ☑ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: This white paper motivates open questions in stellar magnetic activity which X-ray spectroscopy can uniquely address. The answers to these questions are important for stellar astrophysics, but also have implications for exoplanet habitability as well. In the coming decades it will be important to understand the interplay between stars, planets, and planetary systems as a way to make progress in the Search for Life. New observing capabilities are required to go beyond the several tens of normal stars which *Chandra* has gathered at high spectral resolution over its two decades of operations. Specific stellar astrophysics questions include determining what controls accretion and magnetic activity in young stars; what factors control the coronal emission of stars; how the characteristics of flares change with time; and how stellar winds change with time. Answers to these questions have implications for where planets form and whether they are potentially habitable.

Understanding the fundamental aspects of stellar structure and evolution was a major success of 20th century astrophysics, yet the field of stellar astrophysics continues to grow and expand as new discoveries challenge that understanding. This will be especially true in the next decade, as the Search for Life will require advances in several interrelated fields. Furthering research in stellar magnetic activity is necessary to understand the fundamental processes controlling observable quantities, a necessary first step to the broader exploitation of this stellar knowledge to gauge the impact on stellar ecosystems, including potentially habitable planets. As summarized in the National Academy's Committee on the Astrobiology Science Strategy for the Search for Life in the Universe,

> *Indeed, because the host star has a significant impact on planetary habitability, and the star's activity and luminosity evolve considerably, it will be important to determine and observe stellar activity indicators in systems of all ages and to understand evolutionary pathways, particularly for M-type stars, to feed back into the overall picture of the evolution of habitable terrestrial planets.*

Plasma heating and the processes occurring in the coronae of stars are of fundamental importance in this respect. Decades of study by high energy satellites have revealed the ubiquity of stellar coronae around stars on the lower half of the stellar main sequence. Even on our well-studied Sun the origin of this hot plasma is not settled, yet it is clear that this X-ray-Extreme Ultraviolet emission impacts planetary atmosphere evaporation (Johnstone et al. 2015). Stellar magnetic properties (global magnetic field distributions, coronal levels and variability) cannot be predicted based solely on fundamental stellar parameters (Kochukhov & Lavail 2017). Instead, because magnetic activity signatures are produced as the result of magnetic reconnection, an inherently nonlinear process, an observational approach is motivated. While we have one spectacularly well-studied star, it is a singular case observed at one point in its evolutionary history which has spanned 4.5 billion years to date. Recent evidence even indicates that its magnetic activity cycle may not be representative of other solar-like stars (Metcalfe et al. 2016), further motivating the need to study magnetic signatures in other stars.

This white paper motivates open questions in stellar magnetic activity which X-ray spectroscopy can uniquely address. The answers to these questions are important for stellar astrophysics, but also have implications for exoplanet habitability. In the coming decades it will be important to understand the interplay between stars, planets, and planetary systems as a way to make progress in the Search for Life. Table 1 summarizes the stellar astrophysics questions, measurements needed to answer these questions, instrument capabilities that would enable these measurements, and the implications of the answers for exoplanet habitability studies.

What controls accretion and magnetic activity in young stars?

X-ray emission in young stars is more complex than for sources on the main sequence. We see a significant excess of soft emission in accreting sources (Preibisch et al. 2005), which are surrounded by accretion disks. This emission is typically attributed to a shock where the magnetically funneled accretion stream impacts the stellar surface. Since the shock occurs at higher densities than typically found in the corona, high-resolution X-ray spectroscopy can be used to disentangle the shock and coronal components. However, in TW Hya, the only young star where we can study density diagnostics for several elements and temperatures with current instrumentation, the distribution of densities cannot be explained by the current accretion models (Brickhouse et al. 2010). To do this experiment, we at least need to measure line flux ratios from different elements in different ionization stages (effective area an order of magnitude higher than *Chandra/HETGS* would allow a sample size of a few dozen targets); but in the end, we really need to resolve kinematic components in the lines to distinguish accretion flows, static coronal structures, and outflows. Young stars not only accrete mass but they also gain angular momentum. Thus the magnetic coupling of the accretion streams to the disk provides an energy reservoir that can power X-ray/Far-UV (XFUV) emission. This emission can penetrate deep into the disk and alter the chemistry in regions where planets are building up. The magnetic connection also allows the star to launch outflows, to spin up or down, and to provide feedback to the inner disk region, potentially changing the disk life time and thus the time that planets have to form.

What stellar factors control coronal emission?

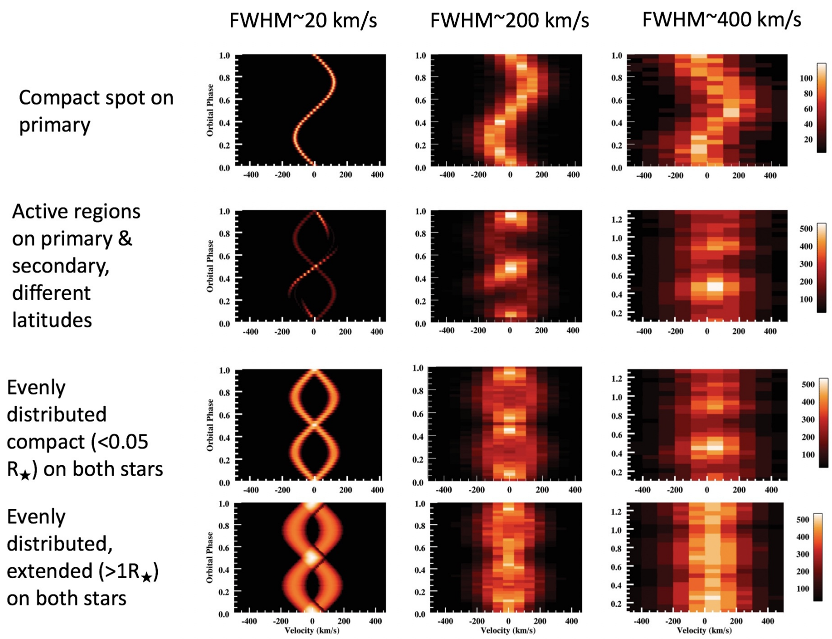

Figure 1: *Figure 10 of Hussain et al. (2012), showing the impact of spectral resolution on the ability to deduce coronal structures and the contribution from each member of a binary, for the nearby M dwarf binary YY Gem.*

Changes to the quiescent coronal emission of stars occur over both evolutionary and shorter timescales. The well-known stellar activity-rotation-age relationship can predict a rough level of a star's X-ray emission given its age and internal structure (Wright et al. 2011). The star's magnetic field creates an ecosystem which helps to set the environment that planets (and life) experience (Lingam & Loeb 2018). Changes in the star's X-ray to EUV luminosity with time directly affect erosion of planetary atmospheres (Johnstone et al. 2015). Stellar magnetospheres influence the inner edge of the traditional habitable zone (Garraffo et al. 2016); thus a fine-grained approach to understanding the structure of stellar magnetospheres and influence on conditions for habitability is required. Recent studies have demonstrated that stellar twins are not magnetic twins: stars with essentially identical stellar ages, masses, radii, and rotation periods have different large-scale and local magnetic field topologies (Kochukhov & Lavail 2017), with consequently differing levels and amounts of X-ray variability. X-rays trace magnetic structure directly, provide the "ground-truth" to be compared with extrapolations of photospheric magnetic field structures such as from Zeeman Doppler Imaging (e.g. See et al. 2016), or dynamo simulations (e.g. Cohen et al. 2017). Figure 1 shows the different impact of magnetic field configurations – whether compact or evenly distributed, and the associated scale heights – which can be discerned in velocity space for a binary given sufficient counts and spectral resolution.

Stellar atmospheres are multi-thermal and multi-density, spatially structured, turbulent, dynamic, and contain multiple abundances. Understanding this complexity requires high spectral resolution observations sufficient to disentangle the vast sea of weak emission lines in the 10-60 Å region. A wide bandpass provides access to transitions spanning the range of temperatures found in the corona for accurate determination of the differential emission measure (DEM) distribution. Velocity broadening in line profiles probes turbulence as well as extended spatial structure. Chung et al. (2004) have provided the only evidence to date of excess broadening of a cool star (Algol).

How do the characteristics of flares change with time? Flares on stars are processes that encompass the entire atmosphere of the star, and are the most dramatic energy release processes normal stars experience during their time on the main sequence. Optical results from Kepler, K2, and now, TESS, will provide systematic probes of flare occurrence as a function of stellar properties. The associated X-ray emission is key for understanding the increased planetary atmospheric erosion beyond what is expected based on a star's evolving quiescent X-ray emission. Measuring the maximum plasma temperature, energy, and luminosity on a sample of stars will inform this study; the apparent connection of the distribution of flare energies to magnetic topology (Aschwanden et al. 2014) will characterize the extent of the Solar Analogy; temperatures in excess of 10 MK (up to and exceeding 100 MK) are the domain of high energy X-ray spectra. Energetic particles are a previously unexplored "dark energy" in stellar flares, with implications for stellar particle acceleration and space weather around other stars. Blueshifts in solar flares of up to several hundred km s^{-1} coincide with the start of nonthermal hard X-ray emission from accelerated particles (Antonucci et al. 1990). Similarly, the peak in nonthermal line broadening in solar flares occurs at the same time as the maximum amount of hard X-ray emission (Antonucci et al. 1982). Measuring line broadening and studying its variation with time in stellar flares opens up the study of the space weather environment that stars create.

How do stellar winds change with time? Since the Sun has a feeble mass loss rate ($\dot{M}$), its steady stellar wind does not affect its evolution in middle age. Currently, only indirect measures of stellar mass loss exist on the lower half of the main sequence. Making progress is important for understanding the precise nature of angular momentum loss and mass loss with time. There is suggestive evidence of an increase in mass loss rate with stellar surface X-ray flux (Wood et al. 2015), up until a critical value where $\dot{M}$ decreases precipitously. A high spatial resolution, sensitive X-ray telescope, can provide direct measurements (or upper limits) on mass loss for the nearest stars using charge-exchange emission, as laid out in Wargelin & Drake (2001). Spectra of the emission would confirm the expected spectral signature.

Coronal mass ejections (CMEs) accompany flares on the Sun and cause geomagnetic storms on Earth. They are the major contributor to space weather in our solar system, and are potentially the major contributor to exoplanet space weather in the context of other planetary systems. Scaling between solar and stellar flare energies, and then between solar flares and CMEs, implies that CMEs are potentially a major impact to the stellar kinetic energy budget (Drake et al. 2013), as well as a severe habitability concern. Yet they are not observed as often as they are expected to be on stars (Crosley et al. 2018ab). There are several observational methods utilizing X-ray spectroscopy that can detect and study CMEs on stars: changes in column density during a flare;

Table 1: Stellar X-ray spectroscopy informs stellar and planetary studies

Stellar Astrophysics Question	**Measurement Needed**	**Capabilities Required**	**Implication for Habitability**
What controls accretion & magnetic activity in young stars?	DEM, n_e, N_H, abundances of coronae as function of stellar age, mass, accretion/activity levels	Spectral resolution R>2000†; λ coverage from 10-60 Å; sensitivity	Heating timescale of protoplanetary disks, where planets form, migrate
What factors control the coronal emission of stars?	Broad temperature constraints for DEM analyses as a function of age, rotation, $T_{\rm eff}$, magnetic geometry	Spectral resolution R>2000†; λ coverage from 1-40 Å; sensitivity	Energy balance in corona, extrapolation into XEUV, planetary atmosphere irradiation
	Density constraints at multiple temperatures	Spectral resolution R>2000†; sensitivity	Energy balance, characteristics of magnetospheric structures
	Coronal length scales	Spectral resolution R≥5000 for line broadening, sensitivity	Influence of stellar magnetosphere on habitable zone
How do the characteristics of flares change with time?	Systematic variation of $T_{\rm max}$, $E_{\rm flare}$, $L_{\rm X,max}$ on flares and distributions of flare energies of stars with varying mass, age, magnetic configuration	Spectral resolution at high E >2 keV; large duty cycles with few interruptions; sensitivity	Individualized approach to determining likely planetary atmosphere evolution
	Influence of energetic particles	Spectral resolution R ≥5000 for line broadening, shifts; sensitivity	Space weather, potentially enhanced planetary atmosphere erosion
How do stellar winds change with time?	Detect charge exchange emission to constrain $\dot{M}$ from a steady wind for the nearest stars	<0.5" spatial resolution; sensitivity	Impact on exoplanet conditions, updated stellar astrophysics
	Study stellar coronal mass ejections over a broad range of stars via changes in column density, coronal dimming, and/or velocity signatures in line profiles	N_H: broad λ coverage; sensitivity below 1 keV. Dimming: broad λ coverage; R>2000; sensitivity Velocity signatures: R≥5000; sensitivity	Solar-stellar connection for magnetic activity, habitability, exo-space weather

† Spectral resolution listed is minimum required to reproduce current capabilities; R of 5000 would enable significant advances.

detection of coronal dimming; and velocity signatures in the line profile.

The Future of Stellar X-ray Astronomy: The underlying physical mechanisms producing X-ray emission in stars are complex, yet understanding these processes will play a fundamental role in the next several decades of astronomy as new, multiwavelength telescopes focus on the abundance of planets being detected every year. New X-ray instrumentation technology, which promises significantly higher effective area than can be achieved by the current generation of X-ray telescopes, coupled with high spatial and spectral resolution, will allow for the first time, detailed systemic investigations of a large sample of stars in our galaxy. Such an X-ray telescope would provide an unprecedented view of magnetic activity of planet-hosting stars and, combined with future multiwavelength missions, will play an essential role in the decades-long Search for Life.

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