High-Energy Photon and Particle Effects on Exoplanet Atmospheres and Habitability

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It is now recognized that energetic stellar photon and particle radiation evaporates and erodes planetary atmospheres and controls upper atmospheric chemistry. Key exoplanet host stars will be too faint at X-ray wavelengths for accurate characterization using existing generation and future slated X-ray telescopes. Observation of stellar coronal mass ejections and winds are also beyond current instrumentation. A full understanding of exoplanet atmospheres, their evolution and determination of habitability requires a powerful high-resolution X-ray imaging and spectroscopic observatory. This is the only capability that can: (1) characterize the crucial EUV stellar flux, its history and its variations for planet hosting stars; (2) observe the stellar wind; (3) detect the subtle Doppler signatures of coronal mass ejections.

1 What Conditions Control Exoplanet Habitability?

The rate at which gas is lost from an exoplanet's atmosphere is critical for the survivability of surface water. Atmospheric mass loss can be driven by both thermal and non-thermal processes, which depend upon the radiation and winds of their host stars. The dominant thermal process is hydrodynamical outflow energized by extreme ultraviolet (EUV; 100–912 Å) and X-radiation (0.1–100 Å) that heat the exoplanet's thermosphere and levitate gas against the gravitational potential (e.g. Owen & Jackson, 2012). Photodissociation and ionization of molecules, including water and CO_2, by the stellar UV and EUV radiation increases the mass-loss rate by producing lighter atoms (e.g., H) that are more easily lost to space. Most of the thermospheric heating is by EUV photons but this radiation cannot be observed directly because of interstellar H absorption. The chromospheric UV and FUV are inadequate EUV proxies. The strength and spectral energy distribution of a star's EUV emission instead arises from the transition region and corona. The 30–60 Å range contains many of the same ionization stages that are important in the EUV range. Observing these enables prediction of the EUV spectrum. Detecting the relevant lines in exoplanet hosts requires a high-resolution ($R \geq 5,000$) spectrum feasible with *Lynx* but not with any existing or slated future missions, including *Chandra, XMM-Newton* or *ATHENA*.

The irradiation history of a planet also depends on the host star's rotation rate: faster rotators produce over time radiation doses larger by an order of magnitude or more than slower rotators (Johnstone et al., 2015). To understand the range and likely radiation doses, it is essential to map out the EUV radiation through time for stars of similar ages, but different rotation rates. This requires observations of open clusters with known ages, achievable at high-resolution with *Lynx* and its effective area of 50× that of *Chandra*.

What is Lynx?

NASA Flagship X-ray space telescope concept

- ×50 more effective area than *Chandra*
- ×16 larger solid angle with sub-arcsec imaging
- Grating spectrometer with resolving power $R \geq 5000$
- Microcalorimeter with 3 eV resolution; 0.3 eV resolution at $E < 1$ keV is provided in a dedicated subarray.

The X-ray emission of stars is variable on many time scales especially for M dwarfs, which many astronomers think are the best host star candidates for locating nearby habitable exoplanets. Young rapidly-rotating stars have high X-ray and EUV emission and emit energetic flares. Long-duration monitoring of the optical radiation of G-type stars by *Kepler* shows that high-energy superflares (total energy $E > 10^{32}$ ergs) are likely on a time scale of ~ 500 days for slowly rotating solar-like stars, but are far more common on young G-type stars, and occur as often as 1 per 10 days (Shibayama et al., 2013). Superflares have been observed with energies as large as $E = 10^{35}$ ergs. *Chandra* has observed superflares on M dwarf and young stars, but the high-resolution spectra of superflares and also of more modest flares needed to infer their EUV emission require the *Lynx* spectrometer (see Figure 1).

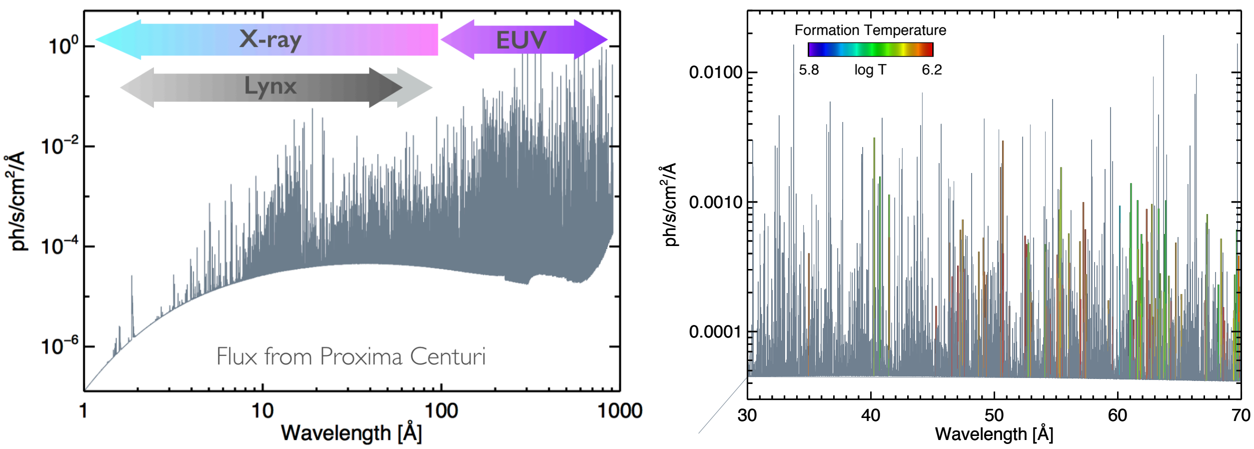

Figure 1: *Left: The key X-ray to EUV spectral region responsible for upper planetary atmospheric ionization, heating and loss. A Proxima Cen flux model is shown, and the approximate Lynx spectral range indicated. The 30-60 Å range exhibits transitions of the same ions that dominate the shorter EUV wavelengths. Right: The soft X-ray range, with EUV flux proxy lines formed at temperatures below* $\log T = 6.2$ *that can be observed by Lynx indicated in color.*

2 Stellar Winds and Exoplanet Atmospheric Loss

The flow of ionized stellar wind electrons and protons erode an exoplanet's atmosphere. Ions produced by photoionization or charge-exchange reactions in the outer atmospheres of exoplanets can be picked up by the magnetic field in the stellar wind and expelled, can be lost through a "polar wind". Simulations show that such wind- and photoionization-driven processes can be a very important mass-loss agent for Earth-like planets around M stars (Garraffo et al., 2016; Dong et al., 2017; Garcia-Sage et al., 2017; Airapetian et al., 2017). Recent measurements by the MAVEN satellite (Brain et al., 2016) confirm previous estimates that the primary mass-loss mechanism for water on Mars is erosion by the solar wind.

The mass loss rates for late-type dwarfs are extremely difficult to measure as the solar mass-loss rate is only about $1.5 \times 10^{-14} M_\odot$ yr^{-1}. Radio observations yield only upper limits. There are indirect estimates of mass-loss rates up to 100 times larger for four G and K stars with stronger magnetic fluxes than the Sun, based on Lyα absorption in the "wall" of hydrogen at the stellar analogy of the heliopause (Wood et al., 2014). There are only two estimates using this technique of mass-loss rates for M stars—$8\dot{M}_\odot$ for the active M3.5 dwarf EV Lac and an upper limit of $< 10\dot{M}_\odot$ for Proxima.

There is a clear need for new techniques for measuring the winds of a much larger sample of stars, including exoplanet hosts, to build a general understanding of exoplanet space weather environments. *Lynx* is the only mission concept that can address this key science question.

The ionized stellar wind interacts with neutral atoms in the ISM and the astrosphere through radiationless collisional transfer of one or sometimes multiple electrons from a neutral ISM atom or molecule to a wind ion. Electrons captured into the upper levels of highly ionized metals cascade to lower levels, emitting X-rays. The resulting X-ray spectrum is dominated by emission from K-shell H-like and He-like ions of C, O, N, and Ne. The conversion to wind mass loss rate is direct. An attempt by Wargelin & Drake (2002) to detect the charge exchange wind signature of Proxima using *Chandra* observations yielded only an upper limit of $3 \times 10^{-13} M_{\odot}$ yr^{-1}. Sub-arcsecond spatial resolution, high sensitivity and low background are required to make detections. With its microcalorimeter, *Lynx* will be able to observe the charge exchange signatures of stars out to at least 10pc for solar-like mass loss rates, and to larger distance for higher rates. Wind properties will be mapped out over stellar activity level and spectral type, and could then be extrapolated to any exoplanet system.

Coronal plasma that is not confined by strong magnetic fields must participate in the stellar wind expansion. With a resolution of 5,000, corresponding to 60 km s^{-1}, and the possibility of measuring flow velocities three times smaller for bright emission lines, *Lynx* will also have the capability to measure stellar winds directly. This would be totally new science that only *Lynx* could accomplish.

3 Coronal Mass Ejections

Strong X-ray flares on the Sun are usually accompanied by the ejection of cooler material (roughly 10,000 K) that had previously been confined by magnetic fields that became disrupted during the flare. The ejected material, generally called coronal mass ejections (CMEs), may also contain high energy protons accelerated in the flare and CME shock front.

Segura et al. (2010) modeled the effect of a superflare ($E \approx 10^{34}$ erg) and CME impact on a hypothetical Earth-like exoplanet located in the habitable zone (0.16 AU) of the flare star AD Leo (dM3e). High energy protons with energies greater than 10 MeV severely depleted nitrogen oxides, and subsequently ozone, in the atmosphere for 2 years. Airapetian et al. (2016) found CME energetic particles can create important prebiotic molecules and alter atmospheric greenhouse gases potentially important for the Faint Young Sun paradox.

These studies demonstrate the acute need for observations of stellar CME events. No such events have been definitively detected, although there are searches underway at low frequency radio wavelengths. Extrapolations of solar CME-flare relationships (Figure 2) are uncertain by orders of magnitude but are sorely needed to understand what CME activity exoplanets are experiencing. High-energy protons are very difficult to observe, but the cooler material in stellar CMEs, or the associated compression wave in the corona, should be observable by *Lynx*. There are two X-ray detections of probable CMEs where the cool, dense material is seen in absorption as it passes in front of the flaring corona: the 20 August 1980 flare on Proxima Cen observed by *Einstein* (Haisch et al., 1983); and the 30 August 1997 superflare on Algol observed by *BeppoSAX* (Moschou et al., 2017).

High-resolution spectroscopy at X-ray wavelengths could routinely and definitively ob-

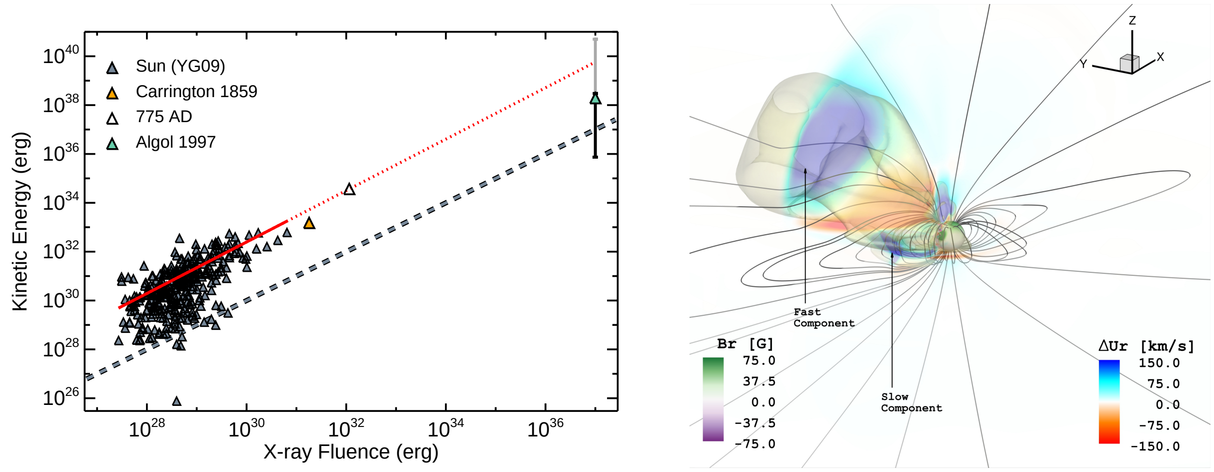

Figure 2: *Left: Kinetic energy vs. associated flare X-ray fluence for solar CMEs. Extrapolating the relation to large events on more active stars is extremely uncertain, requiring definitive CME detections and measurements for characterization. Right: An MHD CME simulation for a moderately active solar-like star (by J. D. Alvarado-Gómez). Plasma is compressed and accelerated outward by the CME front, yielding observable Doppler shifts, ΔU_r, of up to 100 km s^{-1} or so, detectable with the Lynx grating spectrometer for active stars out to 200 pc and inactive stars to 20 pc.*

serve the tell-tale Doppler shifts of CMEs or their coronal compression waves (Figure 2) and identify their physical properties, including their thermal structure, masses and energies. The unique combination of high throughput and high spectral resolution of *Lynx* would be critical, mapping out CME frequency and energy vs optical and X-ray flare diagnostics for nearby exoplanet hosts, and more generally as a function of stellar spectral type and activity level.

4 Transmission spectroscopy of exoplanet atmospheres

X-rays are powerful diagnostics of planetary upper atmospheric gas density structure and chemical composition. The transit of the hot Jupiter HD189733b was detected through X-ray absorption by oxygen in *Chandra* observations by Poppenhaeger et al. (2013), who found that the scale height of X-ray absorbing gas was higher than suggested by optical and UV transits. Hot Jupiters and similar giant close-in planets are important for improving theory and models describing atmospheric loss.

X-ray absorption measures gas *bulk chemical composition* (Figure 3) along the line-of-sight—in this case in the transiting exoplanet atmosphere backlit by the host star's corona. Such measurements are unique to the X-ray range, but only the very closest hot Jupiters are accessible with *Chandra* and *XMM-Newton*. Lynx will be able to observe HD 189733b-like transits out to 140 pc, a factor of more than 300 improvement in survey volume over current missions. Combination with optical/IR data will provide a powerful probe for clouds and hazes that can confuse IR spectroscopic analyses (Sing et al., 2016). By coadding observations of many transits, the *Lynx* calorimeter could also open such studies to larger habitable planets, such as super Earths around nearby M dwarfs (Figure 3).

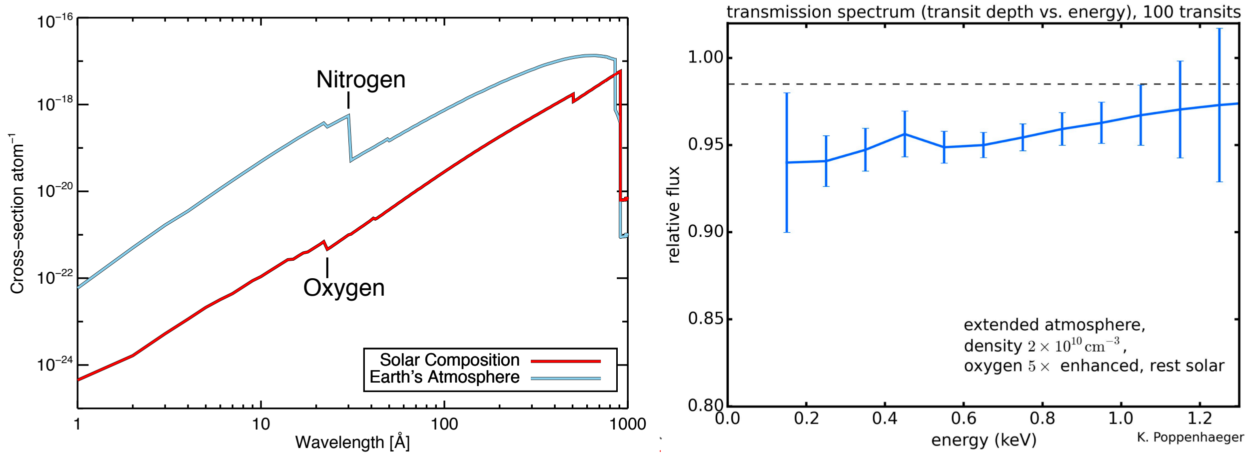

Figure 3: *Lynx will be able to measure gas bulk composition via transmission spectroscopy. Left: Illustration of the enormous difference in X-ray absorption cross-section of gas with solar and Earth's atmosphere compositions. Right: Simulation of detection of the 0.5 keV oxygen absorption edge betraying enhanced O abundance for 100 transits of a superearth planet around an M dwarf (by K. Poppenhaeger).*

5 Summary

- Exoplanet atmospheric loss and evolution cannot be properly understood without a powerful X-ray observatory capable of high spectral resolution of $R \geq 5{,}000$ at soft X-ray wavelengths, a large effective area at least several decades greater than that of *Chandra*, and with spatial resolution better than 1 arcsecond.
- The *Lynx* mission concept would contribute key and unique exoplanet science.

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