Stellar Coronae Viewed with High-Resolution X-Rays: The Impact of the International X-Ray Observatory

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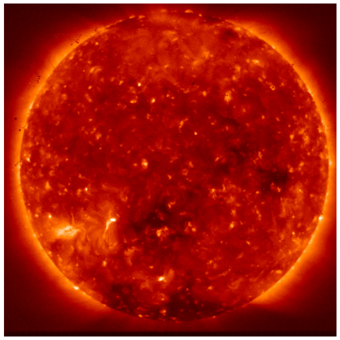
The vast majority of stars (those with masses less than 1.7 solar masses) have X-ray emitting coronae for all but their red giant and later stages of their evolution. Such coronae are believed to be powered by a magnetic dynamo mechanism that results from an interplay between the convective and rotational flows in their outer envelopes, although the details, e.g., whether coronae are predominantly energized by flares, waves, currents, etc., are still actively debated. As stars age, they lose angular momentum through their stellar wind, and their coronae become less powerful, e.g., the present solar corona's X-ray luminosity is only 10^{-7} of its total luminosity, and cooler, e.g., the bulk of the solar corona is cooler than 3 MK.

Because of sensitivity limitations, essentially all operating and previous X-ray observatories with high spectral resolution capabilities have studied primarily the exceptional X-ray luminous coronal stars, such as active binaries and stars much younger than the Sun, i.e., the `tip of the iceberg' of the stellar coronal population. The high-resolution instruments on the International X-Ray Observatory (IXO) will enable us to study the complex, line-rich spectra of a wide range of stellar coronae in unprecedented detail, e.g., with an E/ΔE of 3000, implying a velocity resolution of 100 km/s. We discuss sample programs that IXO could conduct on various classes of stellar coronal sources, and the information that these would yield on coronal abundances, temperatures, electron densities, etc., and potentially on the underlying coronal heating mechanism(s).

In this poster, we will focus on just a few out of the many varied potential coronal science topics that IXO can and will address, based on the projected capabilities of the Calorimeter. A detailed simulation of a study of the active dwarf star AB Dor using the IXO Grating is available at http://space.mit.edu/home/dph/ixo/sim_abdor.html



Hinode XRT View of Sun at Solar Minimum in 0.06-6.0 keV band: actually taken on December 30th, 2008; courtesy of SDAC/GSFC

IXO and Stellar Coronae: Vastly Improved Capabilities

❖For stars, IXO has significant improvements compared to previous X-ray missions with high spectral-resolution capabilities:

- **Excellent Soft X-ray sensitivity**: at energies < 5 keV: IXO will be able to get high-resolution spectra of `normal' stars and low-luminosity objects such as low-activity stars (i.e., solar-like stars at minimum activity levels), planets, comets and brown dwarfs (most of which have soft and faint X-ray spectra): almost all the stars observed with high S/N using the Chandra and XMM-Newton gratings are exceptionally active, many at the saturation limit of $L_x/L_{bol} \sim 10^{-3}$.

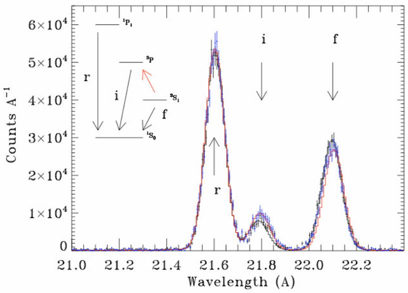
- **Much improved Fe K sensitivity**: at energies > 5 keV where high temperature plasma diagnostics such as Fe K 6.7 keV appear, the IXO Calorimeter will have an effective area A_{eff} of ~6000 cm^2 and a spatial resolution ΔE of 2.5 eV (~ 110 km/s), compared to the Chandra HETG's effective area A_{eff} of 25 cm^2 and spectral resolution ΔE of 30 eV (~ 1300 km/s). Thus, while Chandra has made high-resolution, high S/N observations of a score or so of mostly active coronal binaries in this spectral range, **IXO will be be able to observe many hundreds of stars, including other classes of objects.**

- **High spectral resolution**: many stellar coronae are expected to have phenomena with characteristic speeds of ~ 100 - 300 km/s, e.g., binary star radial velocity amplitudes, jet velocities, flare-related coronal mass ejections, etc., which IXO will be able to resolve

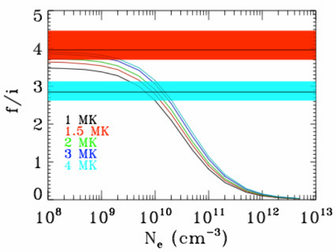
- **Ability to do time-resolved X-ray spectroscopy**: IXO's effective area is such that it can obtain spectra with high temporal resolution (<~ kiloseconds) of moderately bright coronal sources. This will provide the ability to look for variability in the coronal plasmas of temperature, density, Doppler shifts and/or turbulence-broadening on physically meaningful time-scales, such as flare decay or rise times, rotational modulation and/or eclipse durations of active regions, etc.

◎ **Significant hard X-ray capability**: most coronal stars emit very weakly above 10 keV, but there are exceptions, e.g., hyperactive stars like YY Men, stellar flares, protostars, etc. IXO can be used to constrain the existence of nonthermal emission components such as Swift detected in the II Peg 2005 December 16 superflare (Osten et al. 2007, ApJ, 654, 1052).

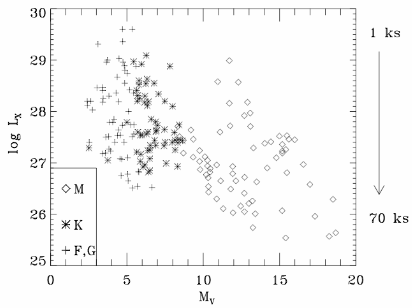
Sample IXO Coronal Science Using the O VII He-like Triplet Density Diagnostics



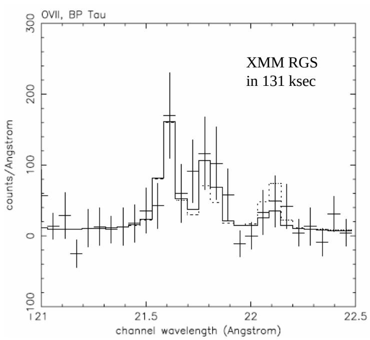
The O VII spectral portion in a 70-ks calorimeter simulation using an input model with the DEM structure of a solar active region, but renormalized to represent a star with an X-ray luminosity of 2 x 10^{26} at a distance of about 5 pc, i.e., a solar minimum star in the solar neighborhood. Two cases are shown: the spectra on the left show 2 contrasting models: the first in the low density limit (black, with black histogram showing the fitted model) and the second, the plasma density is 10^{10} cm^{-3} (blue, with red histogram showing the fitted model). Although the differences in the line profiles are quit subtle, we will be able to discriminate these 2 density cases, as shown in the line diagnostic diagram on the right.

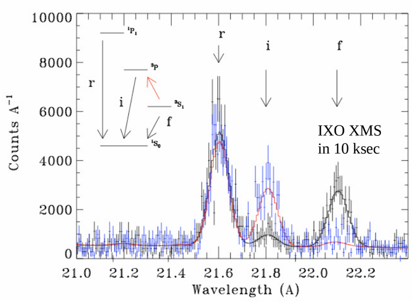


The f/I ratio value for the O VII triplet is plotted versus electron density for the indicated coronal temperatures according to Porquet et al. (2001, A&A, 376, 1113), together with the f/i ratios derived from the simulated spectra on the left, and their 90% confidence bounds. In the first case (shown in red) the O VII emitting plasma is low density (< 10^9 cm^{-3}), while in the second (turquoise), the plasma density is 10^{10} cm^{-3}. It is apparent that this observation allows us to distinguish with confidence between these two cases.



The solar neighborhood F, G, K, and M stars observed by ROSAT, taken from the NEXXUS database of Schmitt & Liefke (2004, A&A, 417, 651), together with the IXO Calorimeter exposure times (shown on the right-hand side of the plot) that would be required to constrain their coronal densities using the f/i ratio of the components of the O VII He-like triplet at 21.6 Å (0.57 keV). **Essentially all of the stars down to log L_x ~ 26 will be observable with the Calorimeter in exposures of 1 - 100 ksec.**





The spectral region of the O VII He-like triplet, but for the case of the Classic T Tauri star BP Tau. On the left is the **131-ks** RGS spectrum described in Telleschi et al. (2007, A&A, 468, 443), from which they inferred an electron density of about 3 x 10^{11} cm^{-3}, with the 90% lower limit of 0.6 x 10^{11} cm^{-3} but, due to the low S/N, no 90% upper limit. On the right we show 2 overplotted simulated **10-ks** IXO Calorimeter spectra of BP Tau, using the plasma characteristics obtained from the RGS spectrum, and two different assumptions for the electron density: the low density case (black data points and fitted model) and the 1 x 10^{12} cm^{-3} case (blue data points and red fitted model).

Outstanding Issues in Coronal Physics and What IXO Will Do

How are coronae maintained and heated? By quasi-continuous (e.g., MHD waves or currents) or by discrete (e.g., an ensemble of microflares) processes? Remember: `one size might not fit all'! Coronal luminosities can range over 8 dex (25 < log Lx < 33), and coronal temperatures over nearly 2 dex (0.1 < T(keV) < 5), and some stars may have additional sources of X-ray emitting plasma such as accretion. **IXO will enable us to do X-ray light-curve and time-resolved spectroscopic studies on a wide range of coronal stars which will help to resolve this issue.**

How are coronae spatially structured? Chandra and other current X-ray observatories have given us insight into coronal temperature distributions (DEMs) but little insight into coronal densities and spatial organization. Coronal structures must be influenced by several factors, including the magnetic field geometry, gravitational and rotational forces, and, in the cases of binary systems containing stars, brown dwarfs and/or giant planets, interactions between the components. **IXO will enable us to study density- and opacity-sensitive line diagnostics, as well as do high S/N eclipse mapping and rotational modulation programs, such as Guedel et al.'s (2003, A&A, 403, 155) XMM-Newton study of α CrB, for a much wider range of objects than previous X-ray observatories have been able to do.**

Do nonthermal processes contribute to non-flaring active coronae? In the sun, power-law hard X-ray emission is observed (typically for seconds to minutes) only during the impulsive phase of large solar flares. Due to limitations of existing X-ray detectors, such emission has so far been observed (Osten et al. 2007) only in one very large flare of the active binary II Peg, where it persisted for about 2 hours, yet we know from radio observations of gyrosynchrotron emission that nonthermal particles are essentially always present in the coronae of active stars, not just in flares. **The Hard X-ray Imager on IXO will enable high S/N observations of many stars in the 10-40 keV range in which power-law emission may be detected.**

Can we disentangle the contributions of coronae and accretion in the X-ray emission of protostars, Herbig Ae/Be stars, and T Tauri stars? The X-ray emitting plasma in the accretion columns of actively accreting stars is expected to be at much higher densities than for standard coronal plasmas, and Chandra and XMM-Newton have found several such cases. **IXO will enable us to study the behavior of density-sensitive line ratios in a much wider range of pre-main sequence stars (see example of BP Tau to the left): we will be able to survey the effects of coronal activity versus accretion in a large sample of nearby star-forming regions.**