MASS-LOSS AND MAGNETIC FIELDS AS REVEALED THROUGH STELLAR X-RAY SPECTROSCOPY

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Stellar X-ray Astrophysics

Although the typical radiative output of most stars at X-ray wavelengths is a tiny fraction of their total luminosity, X-ray emissions provide important constraints on processes which affect the entire stellar atmosphere and even allow insight into dynamo magnetic field generation occurring deep in the stellar interior. X-ray spectroscopy is required for an assessment of the plasma parameters controlling the X-ray flux. Moderate spectral resolution (R=500-1000) of the plasma parameters of stars with Chandra and XMM-Newton have given us a taste of the science that can be done, but constraints on effective area and spectral resolution have limited the number of stars accessible as well as the science which can be extracted. The applicability of the results are limited to the X-ray brightest stars, which tend to be the most anomalous in their other properties. This white paper addresses two key questions of major importance to stellar astrophysics:

- **How do magnetic fields shape stellar exteriors and the surrounding environment, and how does this vary in stars of differing types?**
- **How rapidly do stars lose mass and angular momentum, and how do rotation and magnetic fields affect stellar winds?**

1 Magnetic Fields and Stellar Exteriors

On our nearest star, the Sun, magnetic fields control non-radiative heating mechanisms that heat plasma to temperatures of 10^4—10^6K (characteristic of chromospheres and coronae, respectively), contained in loop-like structures capable of producing spectacular flaring emissions when magnetic reconnection occurs (e.g. Aschwanden 2002). These magnetic fields are produced as the result of dynamo processes at work in the stars' interiors; the dynamo mechanism will differ with the internal structure of the star, i.e. thin outer convection zone or fully convective star, and this affects the geometry of the large-scale fields produced. The magnetic fields in late-type stars are dynamic, producing changes in observed coronal structures and their effects over a wide range of timescales: minutes during large magnetic reconnection flares; fractions of the rotational or orbital period; years or decades of activity cycles; and evolutionary timescales, as non-uniform magnetic flux distributions affect the rate at which angular momentum loss occurs.

X-ray observations of late-type stars probe the tenuous hot coronal plasma produced by non-radiative heating processes. As the hot coronal plasma is confined in magnetic loops, understanding the characteristics of those loops provides knowledge about the dynamo process by providing constraints on the types of magnetic loops generated in stars with varying parameters ($T_{\rm eff}$, rotation, internal structure, field strength and covering factor). High-sensitivity and high spectral resolution X-ray observations are needed to probe the detailed plasma physics of structuring and dynamics. The X-ray bright stars currently accessible to moderate resolution (R=500-1000) X-ray spectral studies are extremely magnetically active and thus the conclusions drawn from their study may not be widely applicable. Observations to explore a much wider range of parameter space, such as age, magnetic field strengths, rotation, metallicity, and evolutionary status are needed; these will nicely complement and extend the solar studies, enabling a more detailed examination of the physics involved in how magnetic fields shape stellar exteriors and the surrounding environment.

Stellar Flares The similar temporal and spectral behavior of X-ray emission during magnetic reconnection flares in a variety of stellar environments provides important clues to the structuring and dynamics of these objects. Recently large X-ray flares have been observed on stars as disparate as active evolved stars (Testa et al. 2007), sub-stellar objects (Stelzer et al. 2006), and young stellar objects with disks (Favata et al. 2005), and the observed temporal behavior of temperature and emission measure appear to follow similar trends as those seen in well-studied solar flares. The interpretation using one-dimensional hydrodynamical loop models developed from studies of solar flares reveals compact loops reminiscent of solar coronal behavior (lengths $\sim 0.1\ R_\star$) on evolved stars, yet larger loops (lengths $\sim R_\star$) on fully convective stars, despite the large differences in pressure scale heights. Magnetic reconnection events can be highly dynamic and involve rapid changes in X-ray-emitting composition, temperature, bulk velocities. To make progress in understanding the effects of magnetic reconnection a more complete assessment of the flaring plasma in a variety of flaring stars is needed. This requires constraints on density, elemental abundance, length scale, and velocity, as well as advances in loop modelling. Diagnostics such as the Fe Kα 6.4 keV fluorescence line probe length scales in stellar flares complementary to hydrodynamic modelling; this has been newly used in the study of large stellar flares on stars without disks (Testa et al. 2007, Osten et al. 2007), but requires sensitive X-ray spectrometers with sufficient spectral resolution around 6 keV ($R \geq 2000$) to extend the diagnostic power of emission from cold iron into the domain of stellar flares. Due to the variety of different effects which operate during a flare (such as particle acceleration, shocks, plasma heating), stellar flares are inherently multiwavelength emitters and coordinated observations across the electromagnetic spectrum are needed to fully understand the flare process. Crucial missing parameters from stellar flare studies are an estimate of the kinetic energy involved in large coronal flares (which can be estimated from bulk coronal motions), necessary to constrain aspects of energy transport and release, and determinations of the nonthermal energy input into the flare process, which can be constrained via nonthermal emission with sensitive ($A_{\rm eff} > 150\ {\rm cm}^2$) hard X-ray detectors at > 20 keV.

The Many Faces of a Star The systematic behavior of X-ray line shifts over the course of several stellar rotations/orbits in short-period active stars (Hussain et al. 2005, Huenemoerder et al. 2006) reveals that stable, large-scale coronal structures exist and can be studied spectroscopically. Current observations are limited to the study of only the brightest objects, integrated over large fractions of a rotation period or orbit, and using only the brightest X-ray emission lines, and thus are highly restricted in the extent to which they can reveal the characteristics of these structures. Better observational constraints are needed to determine the characteristic properties of such stable structures, e.g. temperature, density, and abundance distributions as a function of time during the rotation/orbit, and high spectral resolution observations ($R \geq 3000$) are needed to spectrally disentangle the X-ray emission from the components of binary systems. Such observations done in conjunction with infrared/optical spectral imaging techniques to determine the starspot distribution and

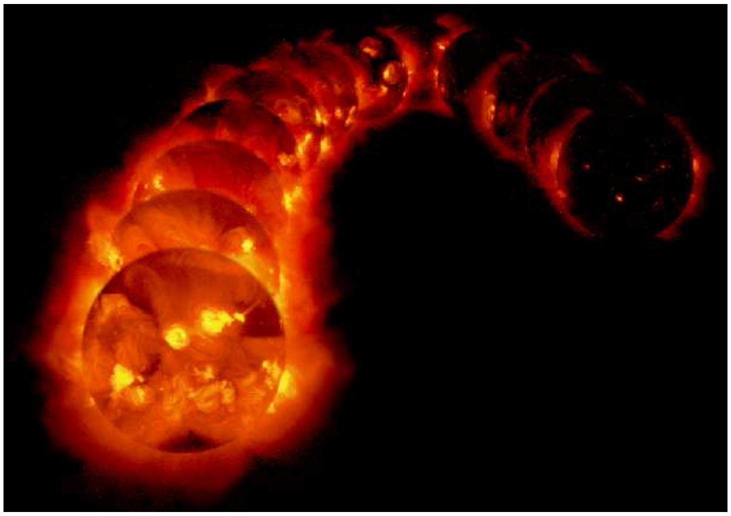

Figure 1: *Yohkoh images of the Sun taken over the course of a solar cycle, illustrating the difference in solar coronal structures from maximum to minimum. Because of the correlation between X-ray emission and magnetic fields, our current capability to study "stars as suns" is limited to those stars with large magnetic filling factors. Large collecting area coupled with adequate spectral resolution is needed to determine the important plasma properties of density and abundance, necessary to infer coronal structures on stars which may be representative of the Sun at its activity cycle minimum.*

photospheric magnetic field distribution, connect the properties of footpoints lower in the stellar atmosphere with the properties of the expanding coronal loops, and allow more inferences to be made about the structuring in stellar exteriors.

"Normal" Stars X-ray bright active stars are known to have high filling factors of magnetic fields on their surfaces, so the observed trends of coronal plasma parameters (temperature, abundance, density) reveal aspects of the nonradiative heating process taking place in regions where magnetic fields are maximally packed with plasma. It is already known that coronal abundance anomalies are a function of X-ray activity, as is the dominant coronal temperature seen in X-ray spectra. However, less active stars have smaller filling factors of magnetic fields and so it is not clear that the same trends will be obtained in objects with lower magnetic activity. Therefore, in order to make progress in understanding the physics of coronal structuring, a range of X-ray luminosities and magnetic field strengths and distributions is needed. The relevant quantities to be determined are the electron densities of the multiple-temperature components, in addition to coronal abundance trends as a function of X-ray luminosity and constraints on coronal loop sizes. These necessitate the use of high spectral-resolution X-ray observations with large collecting area ($A_{\rm eff} > 1{\rm m}^2$) to "connect the dots" between the well-studied Sun and the magnetically hyperactive X-ray brightest stars, by accessing true solar analogs.

Magnetic Fields in Massive Stars The importance of magnetic fields in massive stars has been revealed in the last few years by direct measurements of surface fields up to kG strength (e.g. Donati et al. 2001, Bouret et al. 2008), by the advances in the theory of dynamo in massive stars (Spruit 2002), by the success of stellar evolution models incorporating magnetic fields (e.g. Maeder et al. 2008), and importantly by X-ray observations of some OB stars (Gagné et al. 2005) which require magnetic channeling of wind shocks to reproduce X-ray line profile and temporal behavior. Along with magnetic fields, stellar rotation is required to understand stellar evolution, mass loss, and shaping of the circumstellar medium. The connection between magnetism, rotation, angular momentum, and mass loss is important but largely unexplored partly due to inadequate effective area to observe variability of X-ray line profiles over magnetic cycle and other time scales.

2 Mass Loss

Stellar mass loss is a key parameter which drives stellar evolution in the upper HR diagram and the chemical evolution of the Universe. The history of mass loss plays an important role in determining massive stellar life as it nears the final supernova explosion or gamma-ray burst (GRB). The delicate interplay between stellar magnetism, rotation, and UV field determines angular momentum and mass loss and defines the properties of the supernova or GRB progenitor. Stellar outflows shape the circumstellar medium and thus are pivotal in interpretation and modelling of the interstellar medium (ISM) in OB associations, and the physics of some supernova remnants and GRB afterglows.

Our current ability to constrain mass loss in the upper half of the HR diagram is limited: because of systematic biases, different observational diagnostics in the radio through UV often yield values which disagree with each other by up to an order of magnitude. This produces significantly different outcomes over evolutionary timescales. Observations of X-ray wind line profiles offer the opportunity to help resolve the uncertainties in current determinations of mass loss. Chandra and XMM-Newton have helped break ground by observing a selection of the brightest O, B, and WR stars, but are limited to a small number of the brightest objects. These observations have shown that magnetism in massive stars plays a role in shaping the stellar wind and X-ray emission, that stellar rotation plays an important role in wind dynamics, and that the winds are inhomogeneous (clumped). These key insights in the physics of stellar winds urge new studies which can extend the sample of stars from which such effects can be seen.

X-ray emission lines of hot stars offer a good diagnostic of the characteristics of their stellar winds (Oskinova et al. 2006, Cassinelli et al. 2008). In single stars the f/i ratios of He-like ions measure the location of the X-ray emitting plasma (Kahn et al. 2001), while the line profiles measure the effective optical depth of the wind (Ignace 2001, Owocki & Cohen 2001). Chandra and XMM-Newton spectra of massive stars show that mass-loss rates derived from Hα and radio free-free emission may be overestimated by a factor of two or more because of clumped plasma in the few bright systems that have been studied (e.g. Kramer et al. 2003, Cohen et al. 2006). This overestimate is enough to significantly change the evolution of these stars. Unfortunately the generality of these results cannot be substantiated since very few stars can be observed with the grating spectrometers of Chandra or XMM-Newton. Fully exploiting these important new X-ray diagnostics requires an increase of resolving power and sensitivity beyond that currently available with Chandra or XMM-Newton. Detailed modeling of high signal-to-noise of X-ray emission lines will yield the distribution of hot plasma in the wind, the mass-loss rates, the degree of wind inhomogeneity, and even the geometrical shape of wind clumps. This wealth of information, when obtained for all types of hot stars, will allow us to infer wind properties for the ensemble of OB stars and thus to provide input for stellar evolution codes and allow us to compute the mechanical energy feedback in starburst regions.

3 Measurements Needed

The previous two sections described major questions in stellar astrophysics. X-ray spectroscopic observations are needed to make headway in these areas.

A Complete Assessment of Flare Energetics The bulk and turbulent velocities which are expected to be present during different phases of stellar flares are currently unconstrained; these potentially represent as much energy as in thermal heating and radiation. Another important parameter, the length scales of the flaring coronal loops, is highly model dependent. In order to detect bulk velocity shifts during a stellar flare, sufficient sensitivity and spectral resolution ($A_{\rm eff} \sim 7000$ cm^2 at 6 keV, 3000 cm^2 at 1–2 keV, R=2000-3000) are needed to see the effect of a spectral line shift during the short time in which it occurs; averaging in time will smear out the signal and produce ambiguous results. The shortest timescales of interest in the soft X-ray emission of various classes of stellar flares may be as short as <10-1000 seconds, particularly in the impulsive phase. The velocities associated with blue-shifts, red-shifts and turbulence associated with chromospheric evaporation in the early flare phases are sometimes of the order of 100 - 400 km/s. The Fe Kα diagnostic at 6.4 keV will also be used to determine loop lengths from X-ray flaring loops illuminating the cold stellar surface, placing another constraint on flare dynamics. In order to make constraints on the energy in accelerated particles during stellar flares, sensitive hard X-ray detectors ($A_{\rm eff} > 150$ cm^2) at >20 keV are needed to investigate the spectral shapes of nonthermal emission.

Velocity Information to Infer Coronal Structures Tidally-locked late-type stars in close binary systems are the ideal systems to probe the orbital/rotational dependence of different coronal structures. They can be studied in a relatively complete manner over the course of several adjacent periods to study coherent coronal structures, but with enough sensitivity to probe how those structures change on the relevant timescales. The most revealing information comes from being able to spectrally resolve the two components, and to study the spectra of the two stars and their changes on timescales that are a small fraction, e.g. ∼0.03 of a stellar rotation/orbit, in order to determine changes in the X-ray emission as a function of the period. A grating spectrometer having $A_{\rm eff}$=3000 cm^2 and R=3000 can determine the orbital dynamics and X-ray source location (Figure 2 left), as well as infer rotational broadening, and turbulent broadening.

The Study of Stars as Suns An X-ray telescope with large throughput ($A_{\rm eff} \geq 1$m^2) will enable a complete and systematic survey of "normal" stars and their X-ray emission, avoiding the bright 'active-star' bias present in existing X-ray surveys. One result of this survey would effectively be a study of the Sun as a star in X-rays, since solar mass stars spanning a range of ages from formation until the end of the main sequence and activity levels will be accessible. One of the parameters determined from spectral analysis which reveals important information about coronal structuring is the inferred plasma density as a function of temperature. A sensitive ($A_{\rm eff} \sim 1.5\times10^4$ cm^2) calorimeter with $\Delta E = 2.5$ eV can easily determine the departure from the zero density assumption for helium-like O VII lines to better than 90% on a wide range of cool stars with modest exposure times. Figure 2 right illustrates the range of nearby stars accessible to such a survey, which will enable us to place the Sun in context of other solar-like stars and test the degree and similarity of solar coronal structures to these coronae.

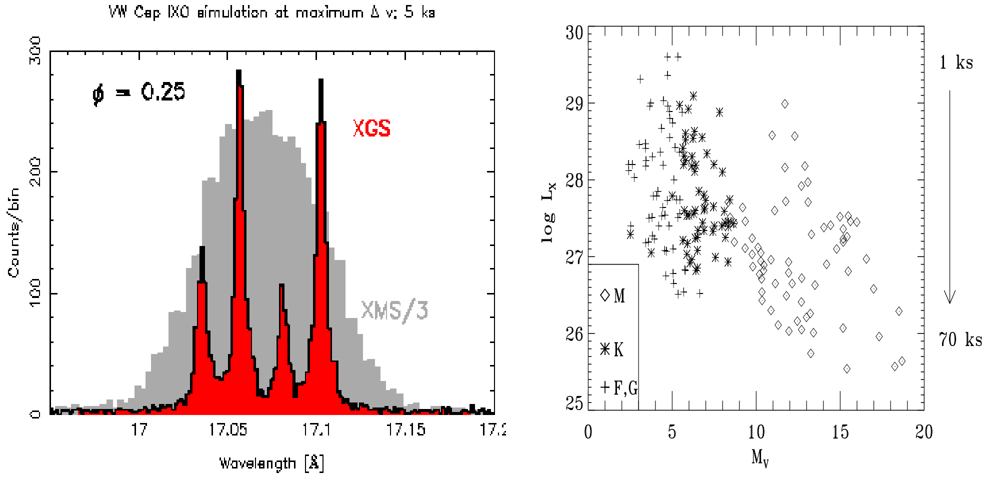

Figure 2: **(left)** *Simulations of the strong Fe XVII lines at 17.05 Å, based on a Chandra/HETGS-derived model (Huenemoerder et al. 2006) for VW Cep, a 0.28 day period contact binary. XGS (red) refers to a grating with R=* 3000*, $A_{\rm eff}$=3000 cm^2, XMS (grey) refers to a calorimeter with 2.5 eV resolution and $A_{\rm eff}$ >1m^2. The emission measure has been divided between the two stars in a ratio of 2:1, and placed at maximum radial velocity separation of 350 km/s. Both lines of the two stellar components are clearly visible.* **(right)** *Distribution of X-ray luminosities for nearby dwarf stars of spectral type F, G, K, and M, from the NEXXUS database (Schmitt & Liefke 2004), along with the range of calorimeter exposure times needed to establish the density of the cool X-ray emitting plasma. Such observations will expand the sample of stars for which constraints on coronal structure are possible, extending to true solar analogs.*

X-raying the Winds of Hot Stars Line profiles are the most powerful diagnostic in the X-ray emission from massive stars. Significant information from line profiles may be extracted with R∼300 if the signal-to-noise ratio of the data is very high. Thus, the principle requirement is for a very high collecting area ($A_{\rm eff} > 1m^2$). This will allow both the expansion of the sample of observable stars and the observation of the brightest stars at very high signal to noise. Figure 3 illustrates the importance of sensitive observations of massive stars as a main key to unlocking the puzzle of mass loss.

Probing Magnetic Fields, Stellar Rotation, and Winds In a magnetically channeled wind shock, plasma which is driven off the star by radiation is channeled along magnetic field lines, leading to 30-50 MK shocks near the magnetic equator. The f/i ratios of helium-like ionic transitions can be used to determine the location of X-ray emission. With large effective area ($A_{\rm eff}$ >1 m^2) time variability studies can be used to explore changes in the strength and shape of these X-ray lines and determine connections between magnetism, rotation, and plasma from the shocked wind. Magnetic fields need to be invoked to explain X-ray properties of Herbig Ae/Be stars (Stelzer et al. 2009) which require high spectral resolution (R=3000) and large effective area ($A_{\rm eff}$ > 1m^2) to study. Mass loss is also a key feedback parameter behind magnetic activity evolution in cool stars; high spectral resolution (R=3000) observations to deduce coronal structures will allow constraints on this process.

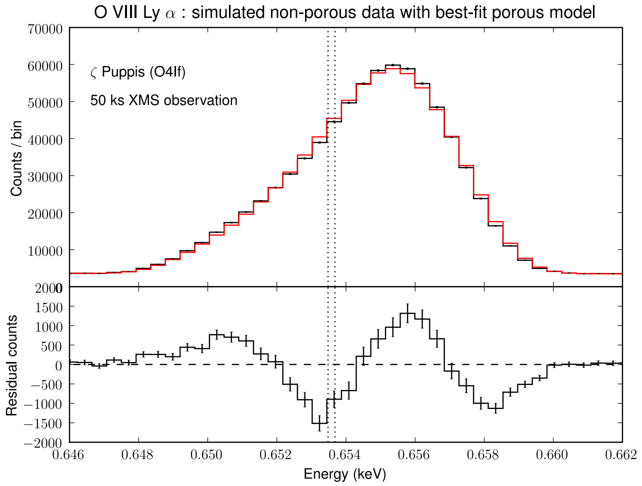

Figure 3: *This figure illustrates the necessity of large effective area (A_{eff} ~1m^2) in using line profile studies of hot stars to probe mass loss and clumping in the winds. The simulated data (plus signs in the top plot) have been generated under the assumption of a homogeneous wind with a moderate mass-loss rate for a 50 ks exposure time using a calorimeter with ΔE = 2.5 eV, while the model (red histogram) corresponds to a clumpy wind with a mass-loss rate twice the data. Both the spectral resolution and sensitivity are needed to see the disagreement in the residuals between data and model in the lower panel.*

The Multi-wavelength Perspective: Complementarity X-ray spectra are a necessary complement to a full understanding of stellar plasmas provided by astronomical observatories spanning the electromagnetic spectrum. Radio observations (such as made with ALMA, EVLA, SKA) constrain the thermal and nonthermal emission from massive stars/colliding wind shock systems as well as nonthermal emission from magnetically active stars. Infrared and optical polarimetric spectra determine via Doppler and Zeeman Doppler imaging techniques the starspot distribution and photospheric magnetic field distribution on rapidly rotating stars, respectively. Flares are a multi-wavelength phenomenon, producing (on the Sun) emissions from gamma-ray energies to kilometer-wavelengths. X-ray observations detailing the plasma heating process and nonthermal energy deposition require simultaneous measures of nonthermal particles at centimeter wavelengths (ALMA, EVLA, SKA), meter wavelength coherent radiation (LOFAR, MWA, LWA), and the optical white-light photospheric response, to make sense of the multiple physical processes and timescales involved in flares. High spectral resolution with high throughput in X-rays will allow great advances in determining the 3D and dynamic nature of MHD phenomena in stars, which are fundamental in understanding their evolution and interaction with their environment. Thus advances in these other wavelength regions must be complemented by advances in X-ray spectroscopy to exploit fully the information content about stellar mass loss and magnetic fields.

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