X-Ray Studies of Stars and Planets with Ultrahigh Sensitivity and Resolution

Science Working Paper for the 2010 Decadal Survey

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1. Introduction

A considerable fraction of the radiation in the universe is X-ray emission arising from hot plasmas. X-ray astronomy's discoveries of bright sources with characteristic X-ray fluxes $F_x > 10^{-13}$ erg/s/cm^2 during the 1960-90s led to profound discoveries of stellar-mass and supermassive black holes and and hot intergalactic baryons. By 1990, X-ray astronomy had generated nearly 15,000 papers garnering 400,000 citations, and the 2002 Nobel Prize in Physics was awarded to one of the field's pioneers. The next major phase of X-ray astronomy emerged with imaging, spectroscopic, and timing studies by NASA's Chandra X-ray Observatory and ESA's XMM-Newton. Complex astrophysical phenomena could now be studied spectroscopically: the X-ray absorption line forest intrinsic to Seyfert galaxies; the interaction between AGN jets and intracluster media; hot winds of starburst galaxies; stellar coronal plasmas; the charge-exchange emission of Mars' exosphere; the X-ray irradiation of protoplanetary disks; and the mysterious flat-topped spectral line shapes of O star winds. Limiting fluxes now reach $F_x \sim 10^{-17}$ erg/s/cm^2. Five thousand observational papers have emerged from these missions and altogether X-ray astronomy has generated over 40,000 studies with 1,000,000 citations.

The current generation of X-ray telescopes is still very small by conventional standards. XMM-Newton, with 4 times the effective area of *Chandra*, has effective area similar to a $14''$ backyard optical telescope. We are now ready for the next stage of X-ray astronomy with a $\sim 20-$fold increase in sensitivity immediately achievable by the International X-ray Observatory (IXO). A roadmap for the development of an additional $\sim 20-$fold increase sensitivity, enabled by mirrors with unparalleled size and precision, and achieving $\sim 0.1''$ spatial resolution and $R \sim 5-10{,}000$ spectral resolution has been presented in the Generation-X (Gen-X) Vision Mission Report (Brissenden et al. 2006). Currently, Gen-X is approved as an Astrophysics Strategic Mission Concept Study (ASMCS). Although not planned for launch until around 2025$-$2030, technology investment will be required during the coming decade to achieve these goals.

An X-ray telescope such as Gen-X will be able to peer into the Epoch of Reionization when supermassive black holes were born, study the cosmic history of black hole mergers, and will probe the behavior of matter in the most extreme environments. Gen-X will also reveal new facets of objects where high-energy processes are only a small fraction of the bolometric emission. Such an X-ray telescope will investigate the atmospheric ablation of habitable planets, the winds and heliophysics of solar-type stars, planet formation processes, and star formation throughout the Galactic disk. The expected capabilities of Gen-X are so advanced that there are not, as yet, successful observations in several of the subjects listed above. Here we highlight a few of these topics to illustrate the unique scientific potential of such an X-ray telescope. The satellite will be capable of advancing existing studies in many fields of stellar astrophysics. Below we outline a few of the scientific problems in stellar astronomy that a high spatial and spectral resolution X-ray mission will be able to address in 15 years.

2. Doppler tomography and elemental fractionation of stellar magnetospheres

Magnetically generated solar phenomena are extremely complex, including dynamos, coronal heating, elemental fractionation, sunspots, flares, helmet streamers, and coronal mass ejections. In other stars, however, particularly rapidly rotating younger and low mass stars, magnetic effects play a much larger role. Considerable progress is being made in mapping magnetic fields on the photospheres of magnetically active stars using rotational modulation of starspots, Doppler imaging, and Zeeman splitting (Donati et al. 2007). The understanding of magnetized coronal regions, however, has required substantial modeling (Jardine et al. 2008). Except for a few systems where coronal structures are rotationally modulated or eclipsed by a binary companion (Favata et al. 2000), our information has been indirect.

The power of Gen-X to expand the sample of stars to a broad population beyond the solar neighborhood is far reaching. G-type stars with X-ray output similar to the Sun could be detected (neglecting absorption) out to ~ 5 kpc or with high-resolution spectra out to ~ 200 pc. Even when pointed towards the Galactic poles, typically ~ 10 solar-type stars will be readily detected in each Gen-X observation. Coronal tomography, using inversion methods familiar from intensity Doppler imaging in the optical band, can then be applied to reconstruct 3-dimensional coronal structure. Rotational phase-resolved X-ray spectroscopy using existing telescopes has been applied to extremely X-ray-bright and rapidly-rotating stars and binaries like AB Dor, FK Com and 44 Boo where Doppler signatures ranging from 30 to 180 km/s are seen (Hussain et al. 2005; Drake et al. 2008). Calculations based on Gen-X capabilities indicate that velocity shifts down to $\sim$1 km/s can be achieved in 1 hour on stars out to 2 kpc with spectral resolution $R = 4000$. One hour resolution provides 2-4% phase resolution for 1-2 day periods on a much wider range of stars than possible even with IXO. X-ray emission from long-lived magnetic loops will be seen from rotational egress to eclipse with Doppler-shifted emission lines and, when observed in concert with ground-based Zeeman-Doppler imaging, X-ray structures and flares will be associated with individual active regions and loop structures. Such data will elucidate the diverse physics of stellar coronal heating, flare physics, and the flow of energy and matter in the surrounding environment.

Gen-X can also extend the study of the Kα fluorescent line in nearly neutral iron at 6.4 keV, a common signature seen during solar flares but only rarely seen in stellar flares with current telescopes (Osten et al. 2007; Ercolano et al. 2008). This line is formed by radiative decay of the excited state resulting from inner-shell ionization either by a photoionizing continuum or perhaps by a collisionally-ionizing non-thermal electron beam. Which of these mechanisms is operative can be determined by comparison of the iron line strength with the hard X-ray continuum. The iron fluorescent line analysis can also give an independent estimate of the physical extent of flaring loops. For Gen-X sensitivities and modest stellar flares, we estimate that 6.4 keV line equivalent widths of ~ 1 eV are expected and observable for source heights $< 10^3$ km above the photosphere. Gen-X can readily resolve the fine structure line doublet (6.391 and 6.404 keV) and measure Doppler shifts of 30 km/s or better. Thus, the dynamics of fluoresced photospheric material, such as its upflow into coronal loops following the flare impulsive phase, can be studied.

3. Stellar winds and their effects on planetary atmospheres

While stellar winds are well-studied when they have mass flows of order $10^{-7} - 10^{-5}$ $M_\odot$/yr, they are very difficult to study in normal solar-type stars. With mass flow of only $\sim 2 - 3 \times 10^{-14}$ $M_\odot$/yr, the solar wind is thought to be accelerated by a complex combination of conductive heating (Parker's 1958 model) and magnetohydrodynamical processes produced by magnetic reconnection flares near the solar surface (Meyer-Vernet 2007). The solar-type winds of a handful of main sequence stars out to $\sim$ 30 pc have been measured indirectly from high-resolution spectra of the Lyα line with HST spectrographs. The observed blue-shifted absorption from excited neutral H atoms is thought to emerge from the shock between the wind and the local interstellar medium, the astropause. But it is a very small effect that requires modeling of the intrinsic stellar emission line, foreground interstellar absorption, and forcing consistency between HI and DI absorption in addition to detailed modeling of the stellar wind itself. Mass loss rates are found from 0.2 to 100 times the solar level but identification of a systematic behavior remains elusive.

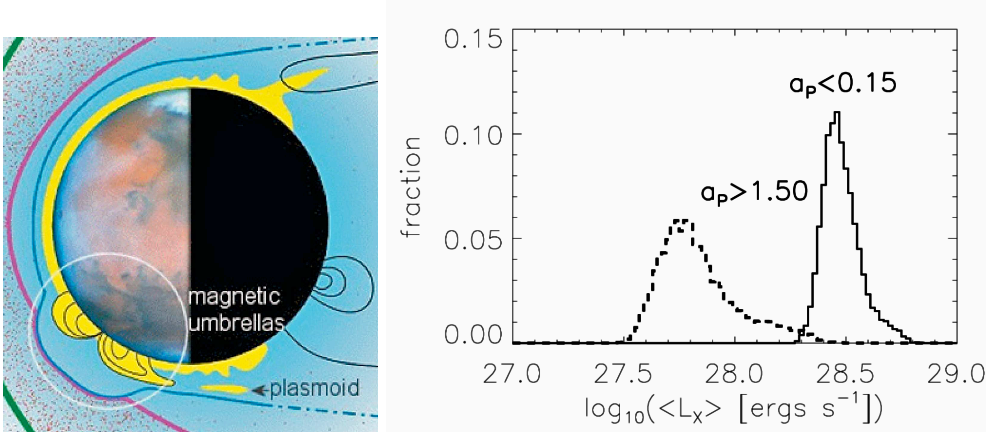

Fig. 1.— Left: Model of ablation of the Martian atmosphere involving the formation and escape of magnetic plasmoids trapping atmospheric gas (Brain 2008). Right: Mean X-ray luminosity of stars with close-in giant planets ($a_P < 0.15$AU) compared to that with extended orbits ($a_P > 1.5$AU). The close-in sample exhibits significantly higher activity levels ($a_p > 1.5$ AU; Kashyap et al. 2008).

It has recently been recognized that a large fraction of the 'soft X-ray background' known for 40 years, historically attributed to thermal emission from the local interstellar medium, in fact may arise from charge-exchange emission lines produced within the solar heliosphere (Lallement 2004). Calculations of the cometary-shaped astropause from solar-type stars (Wargelin et al. 2008) predict that Gen-X will not only readily detect the astrospheric emission but can yield unique quantitative measures of wind speed, wind mass loss rate, interstellar medium density, stellar space motion, and charge-exchange processes.

One critical reason for studying winds in stars of different ages, masses, and magnetic activity levels is their effects on the atmospheres of potentially habitable planets. While the Earth has a strong dipolar magnetic field which largely protects its atmosphere from ablation by the solar wind, the Martian magnetic field is weak and multipolar and its atmosphere is thereby subject to significant solar wind stripping. This is a likely reason why its atmosphere is so thin today. The processes of planetary atmosphere ablation are unclear; Figure 1 (left) shows a recently developed theoretical ablation model. The Mars Atmosphere and Volatile Evolution (MAVEN) probe approved for launch in 2013 will orbit within the upper atmosphere to test this and other models. By the time Gen-X is launched, it is likely that 10^4 exoplanets will have been identified by a variety of ground- and space-based planetary searches, some with atmospheres characterized in the infrared band. The Gen-X satellite's sensitivity will be sufficient to detect astrospheric charge–exchange in some of these systems. We will not only learn a great deal about the generation of solar-type winds, but will be able to directly measure the effects of wind ablation on specific extrasolar planets.

4. Magnetic entanglement of stars and hot Jupiters

Exo-Planetary processes can be very complex and unlike those in our Solar System. This is especially true for Jovian planets that have migrated into orbits very close to a star. Various star-planet interactions have been seen: tidal spin-orbit coupling; hemispheric heating of the planet; evaporation of planetary atmospheres; and, in one case, a correlation of the Ca II HK line emission with the planetary orbital period rather than the stellar rotational period. Recently, a statistical enhancement of the X-ray emission from stars hosting hot Jupiters has been noted (Figure 1 right).

While this last effect can be statistically studied with satellites like eROSITA and IXO, the astrophysical nature of the interaction can only be revealed with the sensitivity of Gen-X. If the excess X-rays are produced in magnetic fields connecting the star and close-in planet, this will be evidenced by orbital eclipses of the field lines. For the brightest known star with a transiting planet, the XMM count rate is 0.07 cps; a flux change of 22% will be required to detect a single eclipse at 5σ significance. A telescope with about 400 times the area of *XMM* will be sensitive to eclipse depths of 1% at 5σ significance for bright X-ray stars with 2 hour transit events. Significant X-ray emitting structures could be resolved on time scales of a few minutes.

5. X-rays and planet formation processes

Solar-type X-rays are known to be elevated during the pre-main sequence phases by factors of $10^2 - 10^4$ over main sequence stars due to intense and frequent magnetic flaring. This is also the epoch of planet formation when a star is straddled by a protoplanetary disk. There is increasing evidence that flare X-rays irradiate the outer layers of the disk, and give rise to Fe 6.4 keV fluorescent X-ray emission – perhaps exciting molecules (H_2, CO, H_2O) and the [NeII] 12.8 μm infrared emission line (review by Feigelson et al. 2007). X-ray ionization of protoplanetary disks is predicted to induce MHD turbulence through the magneto-rotational instability, which in turn may have profound effects on the processes of solid body growth, disk viscosity and dynamics, and protoplanetary evolution. X-rays may thus play a critical role in the processes of planet formation.

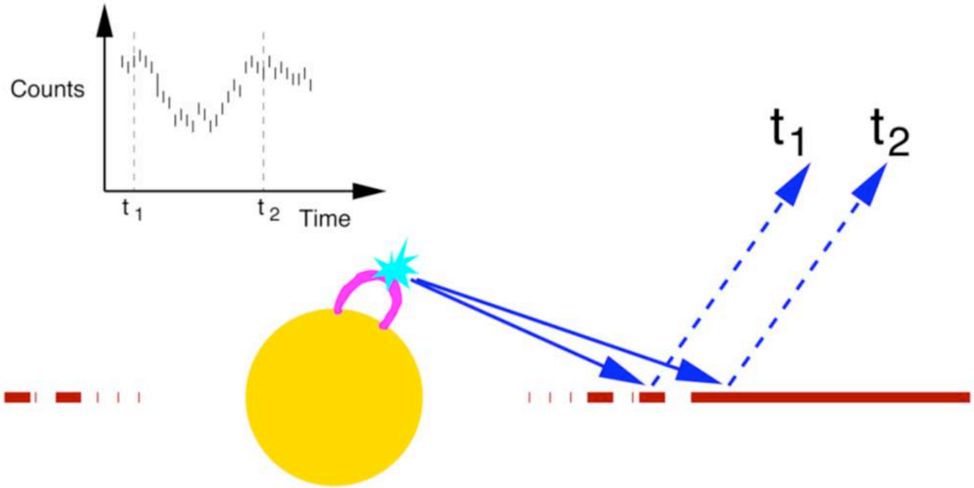

Fig. 2.— X-ray reverberation mapping of protoplanetary disks with the fluorescent Fe 6.4 keV line. Bright flares on the central star are reprocessed by the disk and this signal is revealed in spectra in the light of the cold Fe K fluorescence line. The variations of the flux from this line with time can reveal the location of gaps in the disk where planets are forming.

This possibility is currently based on fragmentary evidence; while most pre-main sequence stars are known to both flare and harbor disks, the spectroscopic signatures of irradiation have been detected in only a few cases. The IXO mission will have $\sim 100-$fold increased sensitivity over *Chandra* in the 6.4 keV line, and can survey the effects of X-ray irradiation in hundreds of young stellar systems. But the yet-higher collecting area of Gen-X is needed to obtain sufficient signal during a single flare to obtain a time series of the 6.4 keV line flux. This provides the opportunity for reverberation mapping of the disk when illuminated by the X-ray emitting structure (Figure 2). The timescales are fortuitously convenient: the flare continuum and ionized 6.7 keV line typically rise in $0.2-2$ hours and fall in $5-30$ hours while the 6.4 keV line will be delayed by the $0.1-7$ hours light travel time across a $1-50$ AU disk surface. Disk gaps and other inhomogeneities should emerge. Gen-X should be able to perform this experiment for a range of protostars and T Tauri stars in the nearby Taurus, Ophiuchus, and Perseus star forming regions. In each case, the overall disk structure, dust and molecular composition will have been measured using the Spitzer, Herschel, JWST, and ALMA telescopes. With radius-stratified X-ray irradiation maps from Gen-X, the physical and chemical effects of X-ray irradiation of disks can be determined.

6. Characterizing massive star formation

The Sun lies in an inter-arm region of the Galactic Plane 8 kpc from the Galactic Center. The local giant molecular cloud in Orion has only $\sim 10^4$ $M_\odot$ of gas producing a few clusters with

$10^2 - 10^3$ stars dominated by an O7 star. But observations of nearby face-on spiral galaxies show that dozens of molecular clouds with $10^5 - 10^6$ $M_\odot$ producing clusters with $\sim 10^4$ stars must be present in our Galaxy. Some moderately large star forming regions lie $\sim$ 2 kpc away, such as the Carina and W3-W4-W5 complexes, but the most massive regions are more distant and heavily obscured. The only superstar cluster which can be studied optically is NGC 3603 (Figure 3a). The Chandra X-ray Observatory observation shown here with a sensitivity $L_x \sim 10^{31}$ erg/s detects many of the OB stars but only $\sim 1\%$ of the flaring T Tauri stars in the cluster. The 500-fold increase in sensitivity and ultrahigh resolution of Gen-X will give nearly-complete samples of the cluster Initial Mass Function (IMF) down to the stellar limit. We estimate that Gen-X will be able to detect and resolve $\sim 20,000$ stars in NGC 3603. Soft X-ray absorption from low-resolution X-ray spectra give accurate absorption measurements for each individual star.

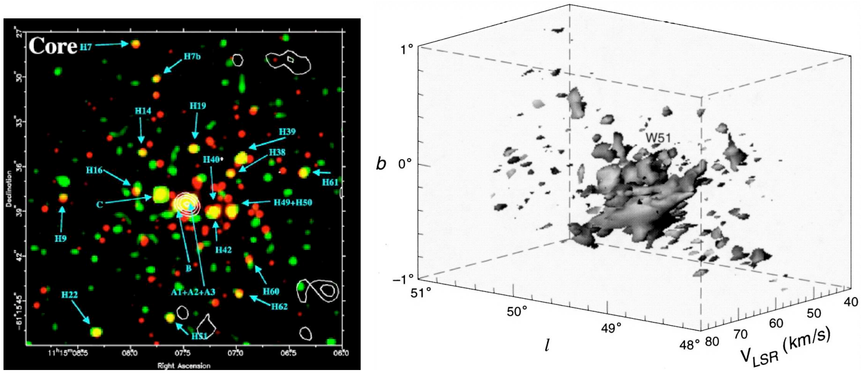

Fig. 3.— Massive star formation regions for Gen-X study. Left: Chandra X-ray Observatory (green, after deconvolution) and Hubble Space Telescope (red) stars in inner $21'' \times 21''$ of the NGC 3603 star cluster at $d \sim 7$ kpc (Moffat et al. 2002). Right: Three-dimensional ^{12}CO map of the W51 giant molecular cloud, one of the Galaxy's most massive clouds with 1×10^6 $M_\odot$, $\sim$20 times the Orion Molecular Cloud (Carpenter & Sanders 1998).

Such studies are particularly important for clusters that are obscured deep in the Galactic Plane. Consider, for example, the W51 massive star formation region, one of the most massive molecular clouds in the Galaxy (Figure 3b). Centered $\sim$7.5 kpc from the Sun, it has molecular clouds and giant HII regions stretched along the tangent line of the Sagittarius spiral arm. Visual extinction of $A_V \sim 24$ mag. to the complex prevents optical study. OB members are easily detected ($K \sim 14$) but are exceedingly difficult to discriminate from the dominant foreground and background Galactic field stars; Okumura et al. (2000) identify only $\sim$ 20 out of $\sim$ 700 bright *JHK* stars as members earlier than B1 in the most concentrated cluster of HII regions, G49.5-0.4, which spans $\simeq$ 30 pc. Thus, the vast majority of stars in the W51 complex, both in space and in mass, can not be discriminated using long-wavelength techniques. In contrast, Gen-X exposures with sensitivity $\sim 10^{-18}$ erg/s in the penetrating $3 - 10$ keV band will have sensitivities better than those achieved with the deepest Chandra exposures of the nearest massive young stellar cluster (the Chandra Orion Ultradeep Project or COUP, Getman et al. 2005) where the entire stellar IMF was detected. It is likely that over 50,000 cloud members, including a complete census of stars with masses $M > 0.3$ $\mathrm{M}_\odot$, would be found in W51 by Gen-X. Galactic field star contamination is strongly suppressed in X-ray exposures in the Galactic Plane because typical stars with ages $2-10$ Gyr have hard X-ray luminosities 0.1% those of pre-main sequence T Tauri stars (Preibisch & Feigelson 2005).

7. Closing Comments

Since Uhuru performed the first comprehensive X-ray sky survey in 1970 and revealed the exotica of the high energy zoo, X-ray astronomy has emerged to address a broad range of astrophysical issues including some relating to normal stars and planets. We discuss here the potential of the remarkable Generation-X telescope, which is ready for technology development during the 2010-19 period and launch in the 2020s. Its ultrahigh spatial resolution, spectral resolution, and effective area will propel planetary and stellar astronomy into directions inaccessible to any contemporary telescope at any waveband. Gen-X is the best follow-up mission to the International X-ray Observatory which is ready for construction today.

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