X-ray Studies of Planetary Systems: An Astro2010 Decadal Survey White Paper

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1. Introduction

It may seem counterintuitive that X-ray astronomy should give any insights into planetary systems: planets, and their natal protoplanetary disks (PPDs), have temperatures which are far too cool ($100 - 1500$ K) to emit X-rays. However, planets orbit stars whose magnetized surfaces divert a small fraction of the stellar energy into high energy products: coronal UV and X-rays, flare X-rays and energetic particles, and a high-velocity stellar wind. In our Solar System, these components from the active Sun interact with the cool orbiting bodies to produce X-rays through various processes including charge-exchange between ionized and neutral components. **The resulting X-ray emission gives unique insights into the solar activity, planetary atmospheres, cometary comae, charge exchange physics, and space weather across the Solar System** (review by Bhardwaj et al. 2007).

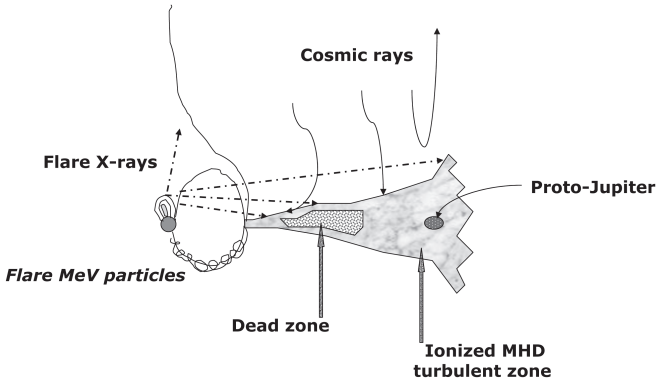

Fig. 1.— *Protoplanetary disk illuminated by flare X-rays and its effects on disk ionization.*

Solar-type stars also universally exhibit enhanced magnetic activity during their youth. X-ray emitting flares in pre-main sequence stars are 100 - 10,000$\times$ more powerful and frequent than in older stars like today's Sun, and this emission only gradually declines over the first billion years on the main sequence (reviews by Feigelson et al. 2007; Güdel 2007). The X-rays and energetic particles from flares will irradiate protoplanetary disk gases and solids (review by Glassgold et al. 2000). As a result, it is possible that **the stellar activity of young stars will substantially affect PPDs and planet formation processes** by heating disk outer layers, producing reactive ion-molecular species, inducing disk turbulence via ionization, and explaining conundrums in the meteoritic and cometary record such as isotopic anomalies, chondrule melting, and radial mixing (see Figure 1). Later, X-ray and ultraviolet irradiation will speed evaporation of planetary atmospheres and thereby perhaps affect planet habitability.

Discoveries of X-rays from Solar System bodies were made with the full range of X-ray astronomical satellite observatories over the past three decades, from the discovery of Jupiter's emission with the *Einstein Observatory* and cometary comae with *ROSAT* to the study today of planets and moons with the *Chandra X-ray Observatory* and *XMM-Newton*. X-rays from young stars are now investigated in thousands of pre-main sequence stars in the nearby Galaxy. Today, ~ 40 papers/year are published on the observations and implications of X-ray emission relating to planetary science. But the X-ray emission is faint, time variable and spectrally complex − today's instrumentation can achieve only a small portion of the potential scientific advances in planetary sciences. The planned high-throughput International X-ray Observatory (IXO) will propel this nascent field forward.

We highlight here five studies in planetary science done using X-ray observations. These

studies address in unique ways several of NASA's strategic goals (Science Mission Directorate 2006) concerning the effects of the Sun on its planets, the physics of planetary ionospheres and ion-neutral interactions, the role of stellar activity on planet habitability, and on the formation processes of planetary systems around young stars. These studies will complement NASA's strong program on Solar System exploration, extrasolar planet discovery, and planet formation environments.

2. Probing protoplanetary disks with the iron fluorescent line

The 19^{th} century insights into the origin of our Solar System involving gravitational collapse of cold gas with angular momentum have been validated in recent decades by the profound discoveries of infrared-emitting PPDs disks around nascent stars in nearby star forming regions and discoveries of extrasolar planetary systems around a significant fraction of older stars in the solar neighborhood. However, a number of enigmatic phenomena have been noted which indicate that non-equilibrium high energy processes play some role in planet formation. Laboratory study of meteorites and *Stardust* cometary material, which record processes in the planetesimal stage of our protoplanetary disk 4.567 Gyr ago, reveal flash-melted chondrules, calcium-aluminum-rich inclusions and free-floating grains with daughter products of short-lived spallogenic radionuclides, and composites with annealed or glassy components (reviews by Connolly et al. 2006; Chaussidon & Gounelle 2006). Infrared spectroscopic studies of some distant PPDs with NASA's *Spitzer Space Telescope* reveal heated and ionized gaseous outer layers (reviews by Najita et al. 2007; Bergin et al. 2007). While some of these phenomena can be attributed to the effects of violent events which precede gravitational collapse (such as supernova explosions), others require irradiation of disks by the X-rays and energetic particles from magnetic reconnection flares around the host young star. X-ray ionization should dominate cosmic ray ionization by several orders of magnitude (Glassgold et al. 2000). X-ray astronomers are thus joining the vibrant community of meteoriticists, infrared and millimeter spectroscopists, and theorists seeking **to understand non-equilibrium processes during the protoplanetary disk stage of planet formation.**

A particularly important consequence of X-ray irradiation of PPDs is the predicted induction of MHD turbulence by coupling the slightly-ionized gas to magnetic fields in a sheared Keplerian velocity field via the magneto-rotational instability. Harder X-rays ($>$ 10 keV) from powerful flares can penetrate deeply into protoplanetary disks, and may reach the PPD midplane where planets form. Astrophysicists are enormously interested in the possibility of turbulent PPDs as it appears to solve certain problems (e.g. gas viscosity needed for accretion, inhibition of Type I migration of larger protoplanets) while it raises other problems (e.g. inhibition of grain settling to the disk midplane, promotion of shattering rather than merger of small solid bodies). Stellar X-rays may also be responsible for the ionization needed to propel collimated protostellar bipolar outflows, for the evaporation of icy mantles in PPD grains, and for ion-molecular chemical reactions in the disks. X-rays may play a critical role in the photoevaporation and dissipation of older protoplanetary disks (Ercolano et al. 2008). Figure 1 illustrates various aspects of an X-ray illuminated PPD.

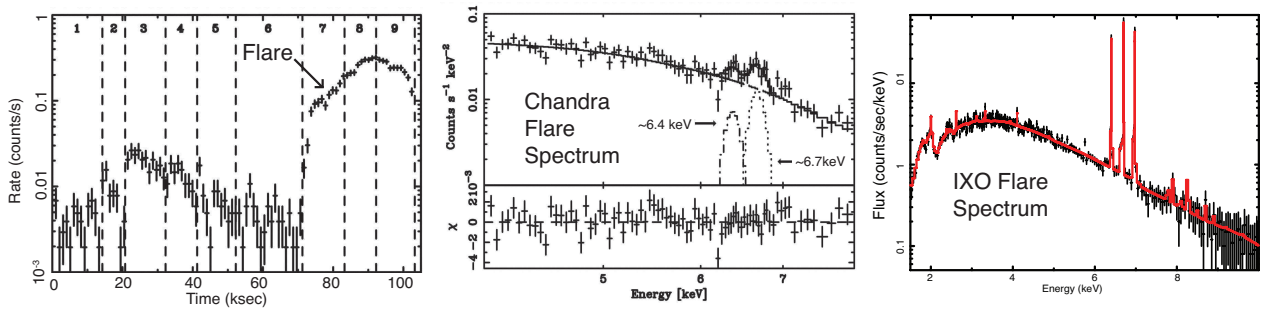

Fig. 2.— *Chandra light curve [Left] and CCD spectrum [Middle] showing the Fe 6.4 keV fluorescent line during a powerful flare from the protostar YLW 16A in the nearby Ophiuchi cloud (Imanishi et al. 2001). The high-ionization emission lines (6.7 keV) arise from the hot plasma confined in the flaring magnetic loop. [Right] Simulation of a 2 ks IXO XMS spectrum at the onset of the YLW 16A flare showing the Fe 6.4 keV fluorescent line. IXO will be able to see flares 100x fainter than currently possible.*

The strongest test of X-ray irradiation of PPDs is the fluorescent iron line at 6.4 keV, which is well-known to appear when a hard X-ray continuum from a central source illuminates cool disk material (e.g., in enshrouded active galactic nuclei and X-ray binary systems). The 6.4 keV emission line has been seen in a few flaring protostellar systems (see Figure 2) but typically lies beyond the sensitivity limit of current instrumentation. With the ~ 200 times improved sensitivity in the fluorescent line compared to *Chandra* and *XMM-Newton*, the IXO X-ray Microcalorimeter Spectrometer (XMS) detector will detect (or place strong constraints on) X-ray irradiation in hundreds of PPDs in the nearby Ophiuchus, Taurus, Perseus and Orion star forming clouds. The IXO Hard X-ray Imager (HXI) will separately establish the intensity of deeply-penetrating X-rays in the $10 - 30$ keV band needed to calculate PPD turbulent and "dead" zones. Prior to IXO's launch, the molecular and dust properties of these disks will be well-characterized by the *Spitzer*, *Herschel* and *James Webb* missions and ALMA telescope. By correlation of X-ray, molecular and solid properties in these systems, IXO should clearly establish the role of X-ray illumination on PPD physics and chemistry. It is not impossible that diversity in X-ray irradiation plays a critical role in the diversity of exoplanetary systems seen around older stars.

3. The complex X-ray emission of Jupiter and Mars

Jupiter is the most luminous X-ray emitter in the Solar System after the Sun. Its emission is complex with several spatially and temporally varying components: charge exchange lines from interaction with solar wind ions, fluorescence and scattering of solar X-rays, and a hard electron brems-strahlung emission (Bhardwaj et al. 2007). Charge exchange is the dominant process where heavy solar energetic ions collide with neutral atoms in the planetary atmosphere, producing a radiative cascade of non-thermal emission lines (e.g. from the $n = 5$ state of hydrogenic O^{7+} at 0.653 keV). In planets like Earth and Jupiter with a strong dipolar

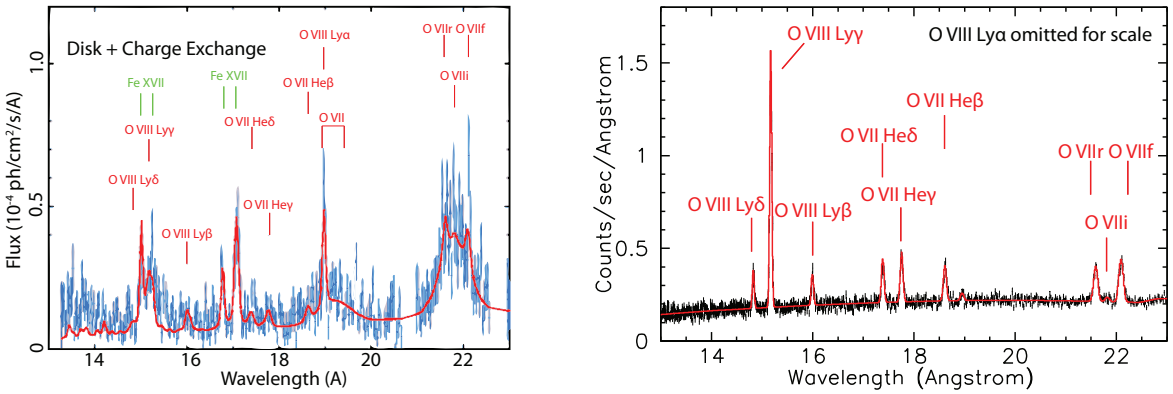

Fig. 4.— [Left] *XMM-Newton spectrum of Jupiter (blue) and a three-component model (red) consisting of auroral charge-exchange lines, solar reflection continuum, hard electron bremsstrahlung continuum(Branduardi-Raymont et al. 2007). [Right] Simulation of a 50 ks IXO spectrum based on the XMM-Newton emission model showing the oxygen charge-exchange emission lines; many more lines are expected.*

magnetic field, these X-ray components are concentrated in auroral regions around the north and south magnetic poles (see Figure 3). K-shell fluorescence from carbon and oxygen is the dominant X-ray emitting process from Venus and Mars where the atmospheres are rich in CO_2 and wind ions are not concentrated toward the poles by strong magnetic fields. High-amplitude variations on timescales of minutes-to-hours can be present in these X-ray components.

Figure 4 shows the best spectra from Jupiter currently available. The IXO spectrum will reveal hundreds of lines with sufficient signal to map the upper atmosphere through the planet's 36 ks rotational period. Repeated visits, particularly at different periods in the solar 11-year activity cycle and several days after powerful solar flares, should show varying ratios of the different emission components elucidating the complex physics of solar-planetary interactions.

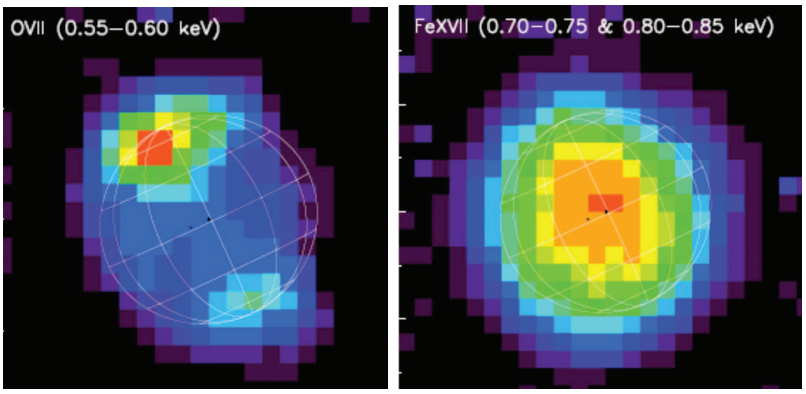

Fig. 3.— *XMM-Newton images of Jupiter in the charge-exchange O VII [left] and fluorescent Fe XVII [right] lines.*

An IXO study of Mars may be particularly important for understanding the evaporative effect of solar X-rays and extreme ultraviolet emission on planetary atmospheres. Martian X-ray emission is dominated by a uniform disk of scattered solar radiation (Mars subtends 18″ at opposition). But remarkably, a faint halo of soft charge exchange lines with unexplained spatial substructure is seen out to $\sim$ 8 planetary radii (Figure 5, Dennerl 2002).

This exceedingly faint X-ray component gives a unique view into planetary exospheres which is inaccessible at other wavelengths. When observed with IXO under a variety of solar wind and flare conditions, the Martian exosphere may provide critical evidence into the complex interactions between stellar X-ray and ultraviolet emission and planetary atmospheres. Indeed, it is possible that Mars' atmosphere is so thin today due to these effect when solar magnetic activity was greatly elevated ~ 4 Gyr ago.

4. Cometary charge exchange

During their perihelion approach to the Sun, cometary ices (mostly water) are evaporated into a large neutral coma which produces strong charge exchange reactions when it interacts with highly-charged solar wind ions (Cravens 1997). X-ray studies provide unique information on this wind-coma interaction region giving insights into charge exchange processes, wind-coma hydrodynamics, and cometary outgassing. Interpretation of cometary X-ray spectra today is complicated as it depends on the solar wind velocity, density and composition, as well as wind ion penetration into the coma, ion-molecular cross-sections, and collisional opacity. These issues can be elucidated by IXO XMS studies (note that grating observations are not feasible due to the spatial extent). X-ray luminosities range from $10^{14} - 10^{16}$ erg/s depending primarily on the comets' encounters with different solar wind states (Bodewits et al. 2007). Several periodic comets and an unknown number of distant comets will enter perihelion during the IXO mission. Spectra will resolve about a dozen charge-exchange emission lines from oxygen above 0.5 keV, and dozens of lines from other elements. Line ratios will change with cometary gas species, solar wind ion composition and wind speed.

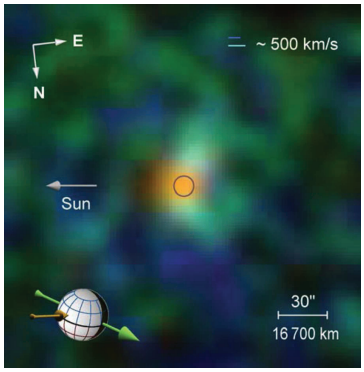

Fig. 5.— *Image of Mars in X-rays derived from XMM-Newton observations: charge exchange $O^{+6}-O^{+7}$ lines in blue, $C^{+4}-C^{+5}$ lines in green, and fluorescent lines in yellow (Dennerl 2006).*

5. Heliospheric charge exchange

X-ray astronomers have increasingly recognized that a significant fraction of the all-sky soft X-ray background arises from time-dependent heliospheric charge-exchange reactions between highly ionized solar wind atoms and interstellar neutrals which penetrate deeply into the heliosphere (Snowden et al. 2004). This has profound implications for our understanding of the Local Hot Bubble and the structure of the Galactic interstellar medium. Earlier X-ray missions also suffer from contamination by charge exchange emission within the terrestrial magnetosphere (Wargelin et al. 2004), but IXO will avoid this component from its location at the Earth-Sun L2 Lagrangian point. From study of the background of dozens of observations with different lines-of-sight through the heliosphere under different solar wind conditions, IXO spectra should provide powerful insights into heliospheric physics and its interactions with its ambient Galactic medium.

6. Atmosphere evaporation in extrasolar planets

Past studies of solar-type stars indicate that X-ray luminosities drop roughly 10-fold between ages of 10^7 and 10^8 yr, another 10-fold between 10^8 and 10^9 yr, and more rapidly between 10^9 and 10^{10} yr (Preibisch & Feigelson 2005). This enhanced X-ray emission during early epochs, and the associated extreme ultraviolet emission which is more difficult to study in young stars, will dissociate and ionize molecules in planetary thermospheres and exospheres so that light atoms escape into the interplanetary medium (Güdel 2007; Penz, Micela & Lammer 2008). Solar wind and flare particles may also erode the *entire* atmosphere if no magnetic field is present. These processes were probably important on Venus, Earth and Mars during the first 10^8 yr and are presently leading to hydrodynamics escape of the atmospheres in extrasolar "hot Jupiters." The atmospheric conditions, and hence the habitability, of planets may thus be regulated in part by the evolution of the ultraviolet and X-ray emission of their host stars. Thousands of extrasolar planets will be known by 2020 through NASA's *Kepler* mission and other planetary search programs. IXO can measure both the quiescent and flare activity of specific stars which will be known to have planets in their habitable zones. Combined with stellar activity evolutionary trends and planetary atmospheric modeling, IXO findings should give unique insights into the atmospheric history of these potentially habitable planets.

7. Summary

X-ray studies of planetary systems are beginning to provide important insights into planetary astrophysics which are inaccessible at other wavelengths. X-ray observations of the host stars reveal the high-energy inputs to protoplanetary disks and planetary atmospheres due to stellar winds and violent magnetic flaring. X-rays from Solar System planets are faint but reveal considerable complexity, a situation well-matched to IXO's high-throughput and high spectral resolution. Charge exchange line emission from interactions between solar wind ions and atmospheric neutrals, along with other processes, are seen in the atmospheres of Jupiter, comets and other Solar System bodies. The X-ray discovery of the Martian exosphere points to evaporation of planetary atmospheres unprotected by magnetic fields, which may play an important role in the habitability of planets. X-ray and infrared spectroscopic studies of protoplanetary disks show that X-ray ionization is present, and theoretical calculations indicate its importance to disk thermodynamics, chemistry and dynamics. It is possible that X-ray illumination is a critical regulator to the formation and early evolution of planets in the disk, but higher sensitivity is needed to study the crucial 6.4 keV fluorescent line. X-ray studies of cometary coma charge exchange, charge exchange distributed throughout the heliosphere, and of stars hosting extrasolar planets are examples of a wealth of IXO studies which will revolutionize this field.

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