How do high energy processes affect planetary formation and habitability?

While it may seem counterintuitive to use X-rays to probe planetary systems, X-rays from young stars have been studied in thousands of pre-main sequence stars in the nearby Galaxy with Chandra and XMM-Newton (e.g. Getman et al. 2005; Güdel et al. 2007). Past X-ray planetary studies necessarily concentrated on the detection of faint emission, temporal variations induced by solar and stellar flares, and crude spectral analysis. However, the field will be propelled forward by IXO, complementing NASA's strong program on Solar System exploration, extrasolar planet discovery, and planet formation environments during the 2000-2020 era.

As a dense molecular cloud core fragment collapses around a nascent protostar, high angular momentum material forms a neutral, molecular Keplerian disk where interstellar solids likely coagulate and grow into planetesimals and planets. This basic model has been validated by the profound discoveries of infrared-emitting protoplanetary 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. Close to Earth, the Stardust mission samples showed 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 in meteorites and cometary material (reviews by Connolly et al. 2006; Chaussidon & Gounelle 2006). Further away, Spitzer has revealed some protoplanetary disks have heated and ionized gaseous outer layers with non-equilibrium molecular abundances (reviews by Najita et al. 2007; Bergin et al. 2007).

Some of these phenomena may be explained by irradiation of disks by X-rays and energetic particles from magnetic reconnection flares around the host young star (e.g. Feigelson et al. 2002; Stäuber et al. 2006; Glassgold et al. 2007; Miura & Nakamoto 2007). One consequence of X-ray irradiation of protoplanetary disks may be particularly important: harder X-rays (5-20 keV) from powerful flares can penetrate deeply into protoplanetary disks, and the resulting molecular ions couple to disk magnetic fields (Igea & Glassgold 1999). Combined with the Keplerian shear, this situation induces the magneto-rotational instability, which quickly produces turbulence.

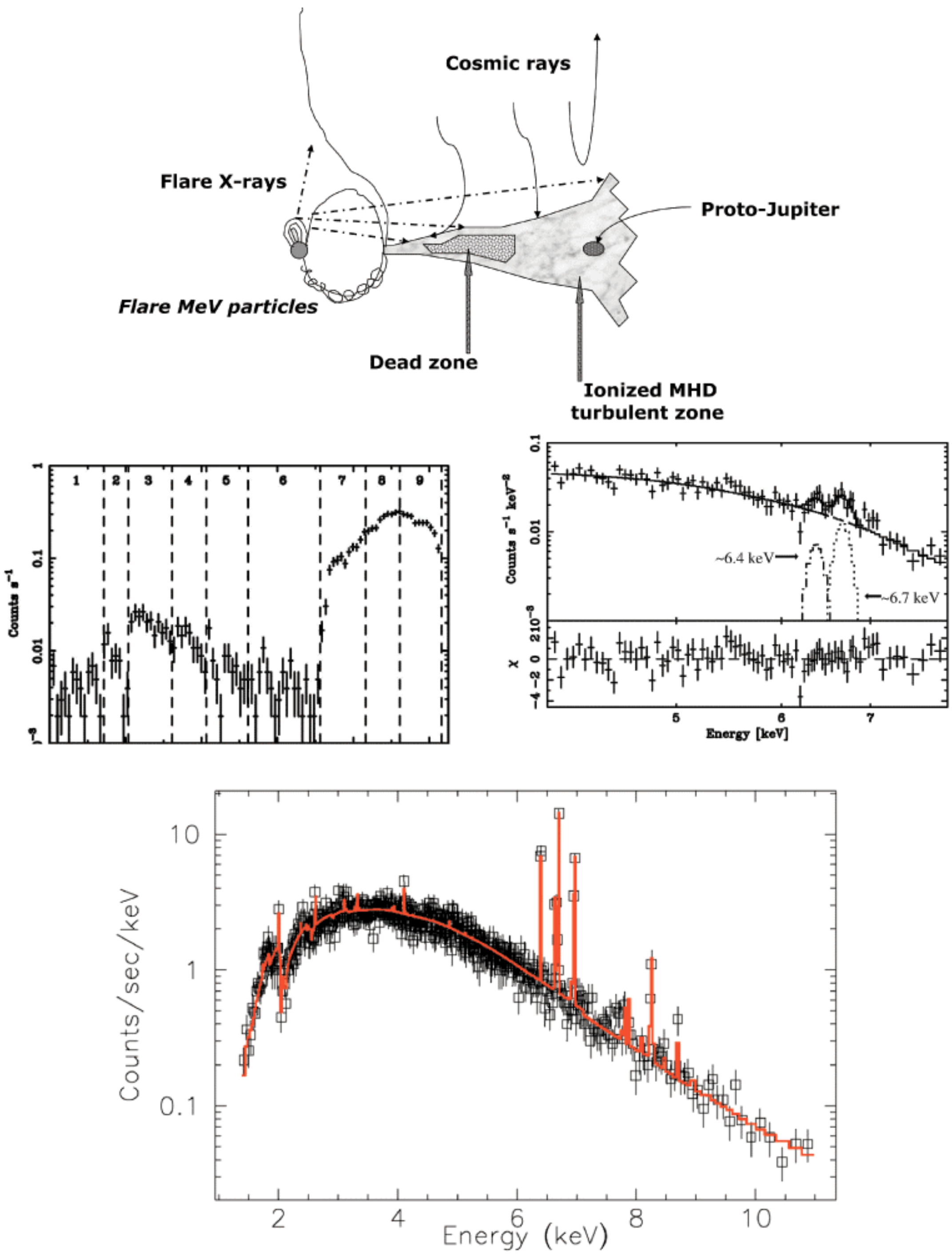

Figure 1. **Protoplanetary disk fluorescence. Top: Diagram of the illumination of the protoplanetary disk by flare X-rays and its effects on disk ionization. Middle: Chandra light curve (left, 100 ks duration) and CCD spectrum (right) showing the Fe 6.4 keV fluorescent line during a powerful flare from 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. Bottom: Simulation of a 2 ks IXO calorimeter spectrum at the onset of the YLW 16A flare showing the Fe 6.4 keV fluorescent line. The structure of the disk can be inferred by reverberation mapping using a times series of such spectra.**

Astrophysicists are interested in the possibility of turbulence in protoplanetary disks 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). flare X-rays may also be responsible for the ionization needed to propel collimated Herbig-Haro outflows that are ubiquitously present in protostellar systems (Shang et al. 2002). The figure below (top panel) illustrates various aspects of an X-ray illuminated protoplanetary disk.

In the context of protoplanetary disk astrophysics and planet formation scenarios, it is important that we test the effects of stellar flares and X-ray irradiation on protoplanetary disks. This is best achieved through study of the fluorescent iron line at 6.4 keV, which is well-known to appear when a hard X-ray continua 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 (Tsujimoto et al. 2005; Favata et al. 2005) but typically lies beyond the sensitivity limit of current instrumentation. With its improved sensitivity compared to Chandra and XMM-Newton, an IXO survey of the nearby Ophiuchus, Taurus, Perseus and Orion star forming clouds will detect (or place very strong limits on) X-ray illumination for hundreds of disks. Molecular and dust properties of these disks will be well-characterized by the Spitzer, Herschel and James Webb missions and ALMA telescope to complement the IXO findings.

During these surveys, particularly of the rich nearby Ophiuchus cloud, a few 'superflares' with peak X-ray luminosities around 10^{32} erg/s will be seen. (For comparison, the contemporary Sun produces occasional flares up to 10^{28}-10^{29} erg/s.) When a superflare illuminates it surrounding protoplanetary disk, the disk structure can be inferred by reverberation mapping. The figure above (middle panels) shows one of these events and its Fe 6.4 keV emission line as seen with the Chandra X-ray Observatory (Imanishi et al. 2001). The lower panel shows a simulation of the IXO calorimeter spectrum obtained in 2 ks after the onset of this flare with ~100 counts/ks in the fluorescent line. A time-series of the line intensity over the following few hours would reveal the disk structure as viewed by the X-ray emitting magnetic loop with ~2 AU (= 1 ks light travel time) spatial resolution. Combined with space-based and ground-based (e.g., Keck mid-infrared adaptive optics, ALMA) data, detailed portraits of these particular X-ray illuminated protoplanetary disks will emerge.

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