X-Ray Flares of Sun-Like Young Stellar Objects and Their Effects on Protoplanetary Disks

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Abstract.
Astronomical observations of flares from analogs of the early Sun have the potential to give critical insights into the high energy irradiation environment of protoplanetary disks. Solar-mass young stellar objects are significantly more X-ray luminous than the typical low-mass T Tauri star. They undergo frequent strong flaring on a several day time scale. Very powerful flares also occur, but on a longer time frame. The hard X-ray spectrum of these stars become even harder during flaring. The X-rays from these sun-like young stellar objects have the potential to ionize circumstellar material at a level greater than galactic cosmic rays out to distances \( \sim 10^4 \) AU. Their characteristic hard spectra imply that, on encountering this material, they penetrate to fairly large surface densities of the order of 1 g cm\(^{-2}\) or more. Three specific illustrations are given of the effects of the X-rays: The physics and chemistry of the atmospheres of the inner accretion disks; the ionization level at the disk midplane, important for the viability of the magnetorotational instability; and the nuclear fluence in the irradiation zone just interior to the inner edge of the disk, important in local irradiation scenarios for producing the short-lived radionuclides found in meteorites.

1. Introduction

Ever since the EINSTEIN mission launched in 1978, it has been known that young stellar objects (henceforth YSOs) are strong emitters of X-rays. The X-ray emission exhibits large-amplitude flaring, attributable to violent magnetic reconnection events similar to but far more powerful than those seen on the contemporary Sun. During the 1990s, ROSAT and ASCA provided a wealth of new information on this emission. With better angular resolution, ROSAT was able to measure the soft X-rays from individual sources in nearby young
clusters. ASCA was able to detect hard X-rays, although its low angular resolution led to some confusion as to their origin. Despite these limitations, both observatories were extremely productive. In 1999, new-generation X-ray observatories, CHANDRA and XMM/NEWTON, were launched. In addition to the greater sensitivity associated with large mirrors and detectors, these telescopes have the capability to measure X-rays over a broad range of energies and with good spatial resolution. For example, with its much improved spatial resolution, CHANDRA is ideally suited to study the X-ray emission from the members of young stellar clusters.

Many of the earlier results on the X-ray emission from YSOs were summarized by some of the present authors in reviews written about the time of the launch of CHANDRA and XMM/NEWTON. Feigelson & Montmerle (1999) gave a broad perspective on the observations and their implications, and Glassgold, Feigelson, & Montmerle (2000; henceforth GFM00) focused on the effects of YSO X-rays on the circumstellar environment. In this report, we update the observations with recent results from CHANDRA, especially from a sample of solar-mass stars in the Orion Nebula Cluster or ONC (Wolk et al. 2005) and address issues of particular relevance to this workshop regarding the relation between chondrites and the formation of the solar system. The ONC is the nearest cluster (450 pc distant) that has a full range of stellar and sub-stellar masses, ranging from massive O stars in the Trapezium to brown dwarfs. We also discuss the considerable progress that has been made in understanding how X-rays affect the processes involved in the formation of low-mass stars. We refer the reader to the two above-mentioned reviews for additional details and earlier results.

2. CHANDRA Observations of Solar-Mass YSOs

Numerous papers have already been published from the five years of observing YSOs with CHANDRA and XMM/NEWTON, usually based on exposures lasting \( \sim 50 \) ks. By combining two such observations for a total of 85ks, CHANDRA was able to detect \( \sim 1000 \) sources in the ONC (Feigelson et al. 2002a), with \( > 90\% \) identified as YSOs. In an unprecedented 800,000 s observation in early 2003 over 13 days, the Chandra Orion Ultradeep Project (COUP) detected more than 1600 X-ray sources in a \( 17' \times 17' \) image of the cluster centered on the Trapezium stars in the Orion Nebula (Getman et al. 2005). A large fraction of these sources have been identified as pre main-sequence objects. The long duration of the exposure offers a unique opportunity to study the temporal behavior of YSO X-ray emission. Many of the analyses of the COUP observations will be published in an issue of the Astrophysical Journal Supplements in 2005. We restrict the present discussion to just two of the many new observational findings: (1) a study of the flares of solar-mass YSOs (Wolk et al. 2005), and (2) the detection of fluorescent Fe line emission, presumably by circumstellar disk material (Tsujimoto et al. 2005).

2.1. X-ray Flares from Sun-Like YSOs

Following the strategy of Feigelson et al. (2002b), Wolk et al. (2005) identified a small subset of the ONC X-ray sources as YSOs with masses in the range
0.9 − 1.2 \, M_\odot.\) The sample was defined with the help of the stellar evolutionary tracks calculated by Siess \textit{et al.} (2000) that give approximate ages for the sample members. Most are in the range from 1 − 5 Ma, with a median age of \sim 2 Ma. Figure 1 shows a 2MASS (Two Micron All Sky Survey) infrared photo of the central 12′ of the ONC, corresponding to a scale 1.57 pc at Orion’s distance of 450 pc. The COUP solar-mass stars, observed by CHANDRA with a spatial resolution of \sim 1″, are shown as green circles.

Figure 1. The central part of the Orion Nebula cluster with the COUP solar-mass stars labeled by (green) circles.

The COUP observations confirm previous CHANDRA results (anticipated by the observations of earlier X-ray satellites) that solar-mass YSOs are strong emitters of hard as well as soft X-rays. The “characteristic” X-ray luminosity for the sample has a median value \( L_X \simeq 10^{30} \text{ erg s}^{-1} \) and a distribution that has a spread ±10 about the median \footnote{Instead of quiescent luminosity, Wolk \textit{et al.} (2005) define a characteristic luminosity in terms of Bayesian blocks of the X-ray light curve when the YSO emission is essentially constant, which is about 75\% of the time.}. This absolute level is larger than for most T Tauri stars, which have lower masses. Preibisch \textit{et al.} (2005) show that, for the COUP data on the ONC cluster, the X-ray luminosity increases significantly with stellar mass, roughly as \( L_X \propto M^{1.5} \) for \( 0.1 < M/M_\odot < 2 \), where \( L_X \) is the
present luminosity of the Sun. The exact dependence is a function of the pre-
main-sequence evolutionary tracks used to determine age and mass.

Figure 2 shows an example of the spectrum of a solar-mass YSO. This
particular source (#567) is a 1.2 $M_\odot$, K-type, moderately extincted YSO that
underwent three strong flares during the COUP observation, as discussed below.
It illustrates well the generic features of solar-mass YSO X-ray spectra. First,
the soft X-rays (roughly those below 1 keV) are strongly absorbed by interstellar
matter along the line-of-sight, an effect due to the strong decrease in the X-ray
absorption cross section with X-ray energy, $\sim E^{-2.65}$. Second, the flux level of
the hard X-rays (above 1 keV) is high. Because of the energy dependence of
the absorption cross section, a 1-keV X-ray has an absorption length $\sim 10^{22}\text{cm}^{-2}$,
whereas a 5-keV X-ray has an absorption length $> 10^{24}\text{cm}^{-2}$. These facts are
relevant for the discussion to follow of the environmental effects of the X-rays:
solar-mass YSOs produce X-rays that can penetrate through relatively large
surface densities of matter. This capability is enhanced during flares when the
spectrum hardens.

![Figure 2. X-ray energy spectrum of COUP source # 567 from Fig. 6b of
Getman et al. (2005). The spectrum is fit (heavy solid line) by a conventional
two-temperature model with $kT_1 = 0.8$ keV and $kT_2 = 3.1$ keV (lighter lines).
The residuals present evidence of Ne-Fe anomalies often seen in strong flares.
The sub-keV emission is absorbed out by intervening material with a column
density, $N_H = 2 \times 10^{21}\text{cm}^{-2}$.](image)

Figure 3 shows the light curves of two of the COUP solar-mass stars in the
the Wolk et al. (2005) sample. They are reasonably typical examples in that
they show several flares during the 10-day observing period, where a flare is
defined as a statistical significant large and rapid rise above the characteristic
level. A noteworthy aspect of Figure 3 is that there is evidence here for both
short-duration ($\lesssim 1$ hour) and long-duration flares ($\gtrsim 1$ hour). It should also
be mentioned that the observations are limited in their capability to detect all
but the strongest short-duration flares.
Another consequence of the flare analysis of Wolk et al. is that the flare frequency, one every several days, is significantly smaller than the flare frequency obtained by Feigelson et al. (2002b) for a sample of solar-mass stars selected in a different way. The YSOs in the COUP sample of Wolk et al. have a median peak luminosity of $L_X = 10^{31} \text{ergs}^{-1}$. The peak of the second flare in source #1259 at the bottom of Figure 3 is $L_X = 0.1L_\odot$. This is one of the most luminous YSO X-ray flares observed so far. Many of the flares seen by COUP do not have the classical form consisting of a rapid rise and a simple exponential-like decay. The first flare in source #1259 in Figure 3 is a good example. Perhaps it involved a sequence of events initiated by the first flare.

To summarize, strong flares are common in the COUP YSOs with solar masses. On average, they occur on a time scale of several days. Gigantic flares, such as the event in source #1259 that reached $L_X = 0.1L_\odot$, are rarer and occur on time scales of the order of one year, or perhaps are restricted to a subset of solar-mass YSOs. A last important fact about this flare sample is the strong evidence that the spectra become significantly harder during a flare (Wolk et al. 2005).

### 2.2. Fluorescent Fe Line Emission

Another relevant result from COUP is the detection by CHANDRA of fluorescent Fe-line emission near 6.4 keV from a number of YSOs (Tsujimoto et al. 2005). These authors interpret their observations as indicative of the absorption of hard photons by circumstellar material, probably the disk. The K-shell threshold for Fe ions in low ionization states occurs near 6.4 keV and increases to 6.9 keV for almost fully ionized ions. Not only do CHANDRA spectra of YSOs contain photons ranging up to and beyond this energy range, they often show an unresolved emission feature near 6.9 keV appropriate to the coronal temperatures of the X-ray source. These hard photons are absorbed by circumstellar Fe in low-ionization states which then decay by the Auger process and by fluorescent X-ray emission. Although the probability for fluorescent decay is small for the light elements, it is quite significant for Fe, $\sim 25\%$.

Figure 4 shows the spectrum of one of the seven COUP sources for which the 6.4 keV fluorescent line was detected by Tsujimoto et al. (2005). These sources were found in a control sample of 123 candidates with large hard X-ray emissivities. They all have near infrared colors indicative of disks, flares with amplitudes larger and spectra harder than average for the control sample, and more absorption than average. Tsujimoto et al. argue as follows that the fluorescence originates in a flattened disk. First, it cannot originate in the stellar photosphere, since otherwise it would have been seen in all sufficiently bright COUP sources, rather than only in a few embedded YSOs with strong infrared excesses. Second, it cannot be fluorescence from line-of-sight material, since the column densities (known for each source from the soft X-ray absorption) are too small by a factor of 100. Fluorescence from a spherical envelope can be similarly rejected. The remaining alternative is fluorescence from circumstellar material, i.e., a flattened concentration of material that is efficiently illuminated by the X-ray source but
does not obscure the line-of-sight, e.g., a disk. Other studies support this conclusion. The 6.4 keV fluorescent line had been previously seen with CHANDRA in a few protostars (e.g. YLW 16A in the Ophiuchi cloud; Imanishi et al. 2001). Another COUP Study by Kastner et al. (2005) demonstrates the absorption of X-rays in disks by a correlation between soft X-ray absorption and the inclination of proplyds imaged with the Hubble Space Telescope. Altogether, these observations provide important evidence that YSO X-rays do, at least in some cases, directly irradiate protoplanetary disks.

3. **X-ray Interactions**

X-rays from a sun-like star in the ONC can affect the physical conditions in its immediate environment, as discussed in the earlier review by GFM00. In gauging these effects, one has to keep in mind the possible competition from other ionizing sources such as UV photons and cosmic rays. In a large moderately dense young cluster like the ONC, with a more or less complete range of stars from the brown dwarf limit up to O stars, the intra-cluster radiation field can also play an important role, especially in the neighborhood of the Trapezium stars. Sufficiently close to any given star, however, the X-ray emission from that star (and its companion if any) will dominate. This is probably true as a first approximation, even in the presence of the strong UV radiation produced by the accretion shock on the stellar surface, partly because of the greater absorption of the far UV (912-1100 Å) by small dust particles, atomic C, CO and H₂. In addition, satellite observations show that this part of the UV spectrum of T Tauri stars is relatively weak (e.g., Valenti et al. 2000; Johns-Krull 2000).

Focusing on a parcel of circumstellar matter, the effects of the YSO X-rays arise from the electron cascade initiated by the absorption of a moderately hard (keV) YSO photon by a K or L shell electron of a low-abundance heavy atom or ion. The absorption process itself leaves an excited ion, whose main de-excitation mode is the ejection of more (Auger) electrons with energies of the same order of magnitude as the initial threshold. The energy of these first electrons, photo and Auger, is then degraded in a series of collisions that excite and ionize the main constituents of the cosmic gas, H and He, and also by Coulomb collisions with the ambient electrons. The number of collisions is large, since only 35-40 eV is needed to make an ion pair in a low-ionization gas with cosmic-like abundances. From the point of view of the macroscopic physical properties of the circumstellar matter, the main role of the X-rays is to affect its ionization and chemical properties and its thermal state via electronic collisions. The physical and chemical effects generated by X-ray irradiation are discussed by Maloney, Hollenbach, and Tielens (1996) with extensive references to earlier work.

In order to gain an appreciation of the magnitude of these effects, we calculate the ionization rate at a radial distance of 1 AU from a YSO, ignoring attenuation and scattering to be discussed below. We update the previous discussion of GFM00 by following Glassgold, Najita, & Igea 2004 (henceforth GNI04). Using the median characteristic X-ray luminosity from Wolk et al. (2005) as a scale

²Of course other circumstellar material can scatter hard X-ray photons, e.g., the wind and funnel accretion column.
factor, we obtain,

\[ \zeta = 6 \times 10^{-9} \text{s}^{-1} \left( \frac{L_{\text{char}}}{2 \times 10^{30} \text{erg s}^{-1}} \right) \left( \frac{\text{AU}}{r} \right)^2. \]  

This number is larger than the formula given by GFM00 because we are now using (1) a nominal luminosity appropriate to a sun-like YSO, rather than \( L_X = 10^{29} \text{erg s}^{-1} \) and (2) a smaller low-energy cut-off to the spectrum, 0.1 keV, instead of 1 keV. It is worth repeating that the above X-ray ionization rate at 1 AU is eight orders of magnitude larger than the ionization rate due to galactic cosmic rays in the solar neighborhood, \( \zeta_{\text{CR}} = 5 \times 10^{-17} \text{s}^{-1} \). Thus, if stellar X-rays and galactic cosmic rays are the only external ionization source, X-rays can in principle dominate out to \( 10^4 \text{AU} = 0.05 \text{pc} \), taking inverse-square dilution into account but ignoring attenuation and scattering of both radiations, which in any real application need to be included.

Equation (1) is essentially the same as Eq. (4) of GFM00, except that the attenuation factor has been dropped and new choices made for the parameters. Since the X-ray luminosity of YSOs can change greatly from one YSO to another, as do their other properties, the value of \( L_X \) in Eq. (1) needs to be chosen to fit the particular application under consideration. Furthermore, the effect of the large X-ray ionization rate for solar-mass stars is mediated in applications to thermal and chemical phenomena. For example, \( \zeta \) enters into the ionization equation through the combination \( \zeta/n_H \), so that the disk density distribution is an important factor. Furthermore, the actual ionization fraction usually depends on a fractional root of \( \zeta/n_H \), typically between 1/2 and 1/3 at intermediate densities and probably even smaller at higher densities. Thus variations in \( L_X \) of the order of 10 may change the ionization by only a factor of a few.

The above comparison of the X-ray and cosmic ray ionization rates is relevant for thick dense regions; otherwise far UV radiation (FUV) becomes important. For example, let us compare the above X-ray ionization rate at 1 AU for a solar-mass YSO with the rates at which the interstellar UV radiation field ionizes neutral carbon \( (2 \times 10^{-10} \text{s}^{-1}) \) or dissociates CO and \( \text{H}_2 \) \( (\sim 5 \times 10^{-11} \text{s}^{-1}) \). FUV can dominate X-ray destruction under some circumstances, e.g., at larger distances or for smaller X-ray luminosities. On the other hand, FUV radiation is, almost by definition, unable to ionize hydrogen and helium. Close enough to a YSO, the X-rays tend to dominate.

Because the X-ray spectrum includes a wide range of photon energies, the flux decreases less rapidly with column density than exponentially (Krolik and Kallman 1983). Glassgold, Najita and Igea (1997, henceforth GNI97) gave an improved theory, still in closed form, and Igea and Glassgold (2001) included the effects of scattering in a Monte Carlo calculation of disk ionization, to be discussed below in more detail. Although the formulae in GNI97 remain valid, it is not much more difficult in applications to numerically calculate the total attenuation along the line of sight from look-up formulae or tables of the absorption cross section, as done by GNI04. The most up to date account of the X-ray absorption cross sections is Wilms, Allen and McCray (2000).

In the rest of this section, we consider regions close to the YSO and assume that the most important ionizing radiation comes from the direct X-ray emission of the star, assumed for simplicity to be single. Star formation is a
complex time-dependent process involving several dynamical components, and our understanding of the effects of X-rays is far from complete. We discuss three specific topics of current interest for YSOs of roughly solar mass: the atmospheres of the inner regions of YSO accretion disks, the ionization level near the mid-plane of the disk, and the irradiation zone interior to the disk proper. Extensive studies have also been carried out on the jets of active but revealed YSOs (Shang et al. 2002, henceforth SGSL02). This theory has recently been extended to the radio continuum emission from younger and more embedded sources (Shang et al. 2004). The effects of X-rays on the chemical abundances of disks at large radii have been studied by many authors, e.g., Aikawa & Herbst (1999, 2001), Markwick et al. (2002), and Gorti & Hollenbach (2004), the last with specific emphasis on mid-infrared diagnostics relevant for the Spitzer Space Telescope.

Here we focus on: (1) a novel application to the atmospheres of disks at small radii, (2) the ionization of the disk mid-plane, fundamental for understanding disk viscosity, and (3) the connection between X-ray and nuclear irradiation of material just inside the inner radius of the disk, a situation directly relevant for meteoritics. The effects of X-rays on the physical properties of the funnel accretion flow have not yet been investigated.

### 3.1. Disk Atmospheres

Although there have been numerous theoretical and observational studies of dust in disks, much less attention has been paid to the gas. Most theoretical work on the thermal properties of disks has assumed that the gas and the dust are at the same temperature. However, in the study of how X-rays affect the upper atmospheres of protoplanetary disks, GNI04 found that this is definitely not the case away from the mid-plane (above a few scale heights). Near the midplane, the densities are high enough for the dust and gas to interact strongly thermally. Going away from the mid-plane, the disk becomes optically thin to the stellar optical and infrared radiation, and the temperature of the (small) grains will rise, as does the still closely-coupled gas temperature. However, at still higher altitudes, the gas responds to the strong X-ray flux as the attenuation of the X-ray decreases. Its temperature rises to very large values, much higher than that of the dust. To reach this conclusion, GNI04 performed a self-consistent thermal-chemical calculation to determine the abundances of the gaseous ions, atoms, and molecules that are important for cooling the gas through line radiation. One simplification is the use of the gas density and dust temperature obtained by D'Alessio et al. (1999) in a thermal calculation for a generic T Tauri disk. In principle, the fact that the dust and gas are not perfectly coupled implies that a more general two-fluid model is needed. This is important for the observed properties of the dust, such as the spectral energy distribution, since the vertical variation of the atmosphere, for example the degree of flaring, is strongly affected by the gas temperature and pressure.

Figure 5 shows some of these results for the atmosphere of a T Tauri disk at a radial distance of 1 AU starting from the D'Alessio et al. (1999) model with an accretion rate of $10^{-8} M_\odot \text{yr}^{-1}$. Temperature is plotted against perpendicular
column density measured from the top of the atmosphere. The dashed line shows the dust temperature rising above its midplane value due to the increase in illumination with height of small dust grains by the stellar radiation. The dust temperature undergoes a modest inversion, going from about 140 K at midplane to 450 K at the top of the disk. At a vertical column $\sim 10^{22} \text{cm}^{-2}$, the gas temperature begins to depart from that of the dust and, due to surface heating, eventually manifests a very large temperature inversion. In the top layers fully exposed to YSO X-rays, the gas temperature is of order 5000 K. In between the top of the atmosphere and the mid-plane, there is a warm transition region (500-2000 K) with the interesting chemical property that it is mainly atomic hydrogen but has carbon fully associated into molecules. In such a mixture, the CO rotation-vibration transitions are easily excited because of the large collisional excitation cross sections for $\text{H} + \text{CO}$ inelastic scattering (much larger than for molecular hydrogen). The occurrence of an X-ray heated hot layer on top of a cold mid-plane layer has also been obtained by Alexander, Clarke and Pringle (2004).

The appearance of several temperature curves in Figure 5 reflects the fact that GNI04 considered other surface heating mechanisms in addition to X-ray heating. In particular, they investigated the potential role of heating by the YSO wind interacting with the upper layers of the disk and heating by mechanical processes associated with the outward transfer of angular momentum. Although heating from these processes surely occurs, the theoretical understanding of both is incomplete, and GNI04 treated them phenomenologically. For example, the total wind energy incident on the disk can be calculated for any wind model, but the depth and other properties of the resultant turbulent mixing layer are poorly constrained. In the case of viscous heating associated with angular momentum transport, the most popular mechanism is the magnetic rotational instability (MRI) introduced to disk physics by Balbus & Hawley (1991; see also the review by Stone et al. 2000). It leads to local viscous heating of the usual form,

$$\Gamma_{\text{acc}} = \frac{9}{4} \alpha \rho c^2 \Omega,$$

where $\rho$ is the mass density, $c$ is the isothermal sound speed, $\Omega$ is the angular rotation speed, and $\alpha$ is a characteristic parameter measuring the degree of magnetic turbulence. GNI04 argued on the basis of simulations by Miller and Stone (2000) that midplane turbulence generated Alfvén waves that, on reaching the diffuse surface regions, produce shocks and heating. GNI04 regard $\alpha$ as a phenomenological parameter to be determined by appropriate observations of disk atmospheres. In practice, they lump both surface heating mechanisms together since, by dimensional arguments, they may have similar forms. This parameter $\alpha$ labels the gas temperature in Figure 5.

According to Figure 5, there is a narrow transition region with gas temperatures in the range 500-2000 K, that lies between the chromospheric-like temperatures at high altitudes and the relatively cool temperature at mid-plane. The location and thickness of this layer depends on the strength of the surface heating. The curves illustrate this dependence in the case of a T Tauri disk.

[3]The calculations start at a height where the hydrogen gas density is $10^7 \text{cm}^{-3}$. 

at \( r = 1 \text{AU} \). For \( \alpha = 0.01 \), X-ray heating dominates this region, whereas for \( \alpha > 0.1 \), mechanical heating is paramount. When these ideas are applied to the more actively-accreting T Tauri stars, mechanical heating is required to explain the strength of the CO fundamental emission observed by Najita, Carr & Mathieu (2003). GNI04 concluded that some form of surface heating, such as wind-disk interactions or accretion, is required to explain the observations. This is rather similar to the conclusion reached by SGSL02 and SLSG04 in their study of the jets of large accretion-rate YSOs, where X-rays were found to be more important for ionization than for heating. The hot on cold layer model with a warm interface offers new opportunities for diagnostic probes of the gas in protoplanetary disk atmospheres and for verifying that YSO X-rays are effective in determining their physical and chemical properties.

### 3.2. Near Mid-Plane Ionization and the MRI

The crucial role of the ionization level in disk accretion via the MRI was pointed out by Gammie (1996). The physical reason is that collisional coupling between electrons and neutrals is required to transfer the turbulence in the magnetic field to the overwhelmingly neutral material of the disk. Gammie found that galactic cosmic rays could not penetrate beyond a thin surface layer of the disk at several AU. He suggested that accretion only occurs in the surface of the inner disk (the “active region”) and not in the much thicker mid-plane region (the “dead zone”) where the ionization level is too small to mediate the MRI. Glassgold, Najita & Igea (1997) argued that the galactic cosmic rays could not penetrate the surface region of the inner disk because they are blown away by the stellar wind, much as the solar wind does with solar energetic particles. They showed that YSO X-rays could do almost as good a job as cosmic rays in ionizing surface regions, thus preserving the layered accretion model of the MRI for YSOs. Igea & Glassgold (1999) supported this conclusion with a Monte Carlo calculation of X-ray transport through disks, demonstrating that scattering plays an important role in the MRI by extending the active surface layer to column densities greater than \( 10^{25} \text{cm}^{-2} \).

The result of this first work is that the theory of disk ionization and chemistry is crucial for understanding the role of the MRI for YSO disk accretion and possibly for planet formation. These challenges have been taken up by several groups, largely in the context of layered accretion e.g., Sano et al. (2000), Fromang et al. (2002), Semenov et al. (2004), Kunz & Balbus (2004), Desch (2004) and Matsumura & Pudritz (2003, 2005). Fromang et al. discussed some of the issues that can have a significant affect on the size of the dead zone: differences in the disk model, such as a Hayashi disk or a standard \( \alpha \)-disk; temporal evolution of the disk; the role of a small abundance of heavy atoms that recombine mainly radiatively; and the value of the magnetic Reynolds number. Sano et al. (2000) explored the part played by small dust grains in reducing the electron fraction when it becomes as small as the very small abundance of dust grains. They showed that the dead zone decreases and eventually vanishes as the grain size increases or as sedimentation towards the mid-plane proceeds. Kunz & Balbus

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\(^4\text{GNI04 also suggested that Gammie’s dead zone might provide a good environment for the formation of planets.}\)
(2004) and Desch (2004) have addressed the growth and saturation of the instability itself, in particular the effects of initial assumptions about the magnetic field and the role of various diffusive processes. Matsumura & Pudritz (2003, 2005) have investigated some of the implications of layered accretion for planet formation. For further discussion of the role of the MRI in the formation of the Sun, see the article by Gammie and Johnson, this volume.

Semenov et al. (2004) have employed the most complete chemical model to calculate the mid-plane ionization. Like Fromang et al., they include X-ray ionization following GNI97 and ignore scattering; they also employ too small an X-ray ionization rate for Sun-like stars. They include the effects of galactic cosmic rays at something close to a standard rate ($\zeta_{\text{CR}} \sim 10^{-17}\text{s}^{-1}$) and UV radiation from both the mean galactic field (following Draine 1978) and from the star itself. Following earlier chemical models oriented towards the outer regions of disks (e.g., Willacy & Langer 2000; Aikawa & Herbst 1999, 2001; Markwick et al. 2002), Semenov et al. adopt a value for the stellar UV radiation field that is $10^4$ times larger than galactic at a distance of 100 AU. This choice can be traced back to early IUE measurements of the stellar UV beyond 1400 Å for several T Tauri stars (Herbig and Goodrich 1986). Although the UV flux from T Tauri stars covers a range of values and is undoubtedly time-variable, more detailed studies using both IUE (e.g., Valenti et al. 2000; Johns-Krull et al. 2000) and FUSE (e.g., Wilkinson et al. 2002; Bergin et al. 2003) indicate that it decreases going into the FUV domain and has a typical value, $\sim 10^{-15}\text{erg cm}^{-2}\text{s}^{-1}\text{Å}^{-1}$, that is significantly smaller than earlier estimates. The FUV band is crucial because this is where atomic C can be photoionized and H$_2$ and CO photodissociated.

Confining ourselves to considerations of the inner disk, the issue of whether stellar FUV or X-ray radiation dominates is important for the ionization and chemistry of protoplanetary disks because of the vast difference in the energy of the photons. The most direct consequence is that FUV photons cannot ionize H, and thus the abundance of carbon provides an upper limit to the ionization level produced by the photoionization of heavy atoms, $\sim 10^{-4}$ - $10^{-3}$. Next, FUV photons are absorbed much more readily than X-rays, although this depends on the size distribution of the dust grains, i.e., on grain growth and sedimentation. If we use realistic numbers for the FUV and X-ray luminosities of T Tauri stars, we find that $L_{\text{FUV}} \sim L_X$. The rates used by Semenov et al. (2004) and many other modelers of disk chemistry correspond to $L_X \ll L_{\text{FUV}}$. Therefore, the important study of Semenov et al. needs to be extended to the relevant range in the $L_{\text{FUV}} - L_X$ parameter space. More generally, the disk parameters used to explore disk chemistry, i.e., accretion rate, FUV and X-ray luminosity, etc., should correspond as much as possible to the actual T Tauri stars for which theory and observations are to be compared. Likewise the complete neglect of the FUV in GNI04, initially justified by the large difference between the X-ray and FUV attenuation factors, should also be remedied. The simultaneous treatment of the transfer of the FUV and X-ray radiation is complicated by the fact that the FUV photo-destruction of both H$_2$ and CO proceed by line absorption and thus involves highly nonlinear line self-shielding. The importance of solving this problem is highlighted by the suggestion that oxygen isotope anomalies in meteorites are determined by selective photodissociation of CO determined by
line self shielding (Clayton 2002; Lyons & Young 2004; Yurimoto & Kuramoto 2004; Yin 2004; and Krot 2005, these proceedings).

The level of ionization in the mid-plane of YSO accretion disks is affected by many dynamical and microphysical processes. At present, uncertainties in these processes preclude a definitive quantitative evaluation of the ionized regions of protoplanetary disks. But some overall characteristics are clear. Stellar X-rays and FUV emission are significant sources of heating, ionization, and chemical activity in the inner regions of protoplanetary disks. Although the X-rays penetrate deeply towards the midplane at moderately large radii, they ionize only a shallow region above a neutral “dead” zone at small radii.

### 3.3. Stellar Energetic Particles and Short-Lived Radionuclides

In calculating the production of short-lived radionuclides in the region near and inside the inner disk or co-rotation radius, Lee et al. (1998) invoked ROSAT and ASCA observations of soft and hard YSO X-rays to estimate the fluence of nuclear particles. They converted X-ray to stellar energetic-particle fluxes using observations of the contemporary active Sun. A related calculation was done by Feigelson, Garmire, & Pravdo (2002b) using CHANDRA observations. They estimated that the particle fluxes from active YSOs were $\sim 10^5$ more powerful than in the active Sun. This number reflects the fact that YSO flares are more powerful and more frequent than in the contemporary Sun. They also took into account that the distribution in energy of solar energetic particles is shallower than that of the X-rays. This factor of $10^5$ enhancement in flare particle fluences is sufficient to produce by spallation reactions several important anomalies in the abundances of short-lived radionuclides found in meteoritic CAIs (Lee et al. 1998, Goswami et al. 2001, Gounelle et al. 2001, Marhas et al. 2003, Leya et al. 2003).

The COUP observations of solar-mass YSOs can be used to make similar estimates of the particle fluence in the reconnection ring. From the recent COUP study of solar-mass Orion stars (Wolk et al. 2005) discussed in §2.1, we take the mean characteristic luminosity as $10^{30}$ erg s$^{-1}$, and the mean flare luminosity, duration, and repetition times as $5 \times 10^{30}$ erg s$^{-1}$, $10^5$ s, and 4-8 d, respectively, and estimate the fluence at a distance $0.75 R_x$ (with $R_x = 0.05$ AU, the x-point or co-rotation radius) over 10 years to be,

$$F_X(10 \text{ yr}) = 2 \times 10^{15} \text{erg cm}^{-2}. \quad (3)$$

If we convert from X-ray to proton fluence (for energies greater than 10 MeV) using 0.1 as the conversion factor (e.g., Lee et al. 1998), we get essentially the same result as these authors,

$$F_p(10 \text{ yr}) = 2 \times 10^{14} \text{erg cm}^{-2}. \quad (4)$$

There is of course the caveat that the nuclear irradiation probably occurred at an earlier and very active stage of pre-main-sequence evolution when the X-ray emission might well have have been different. While small samples and high obscuration impede thorough study, CHANDRA observations indicate that the X-ray luminosities and flares of Class I protostars (ages $\sim 0.1$ Ma) are comparable to, and perhaps even stronger than, the emission from Class II and III T
Tauri stars (ages $\sim 0.5 - 10$ Ma) (Imanishi et al. 2001). A weak decline of X-ray emission with age, roughly $L_x \propto t^{-1/3}$, is seen over the 0.1-10 Ma age range spanned by the COUP stars (Preibisch & Feigelson 2005). In any case, all such estimates of particle fluences are uncertain by factors of several at least.

In addition to the inferred nuclear spallation effects, the observed X-rays themselves can directly affect the physical state of the irradiated material, i.e., the proto-CAIs (calcium-aluminum inclusions) and chondrules seen in the earliest solar system solids in chondritic meteorites. According to Lee et al. (1998) and Gounelle et al. (2002), these solids experienced thermal processing episodes for several years before being launched into the primitive solar nebula. These events induced a variety of phase changes, including partial or full evaporation. Powerful flares, such as those at the high end of the flare distribution seen by COUP, may play an important role in the thermal processing of this material because of the larger energies involved and also because of the enhanced penetrating power of the hard photons characteristic of flares.

Most of the YSOs observed in the ONC, including the solar-analog sample of Wolk et al. (2005), are revealed T Tauri stars with a median age of 2 Myr. Although a fair fraction have disks and are still accreting, most of the mass has already been accreted following earlier more active stages that occurred during the first several hundred thousand years of their lives. It is very likely that the nuclear irradiation that led to some if not many of the short-lived radionuclides occurred in this early period and not during the T Tauri phase$^5$.

4. Summary

X-ray observations of YSOs with the current generation of large X-ray telescopes, i.e., CHANDRA and XMM/NEWTON, provide much of the information needed to study the effects of the X-rays on the formation of these stars. An extended 10-day observation, the CHANDRA Orion Ultradeep Project (Getman et al. 2005), has helped clarify our understanding of the temporal variation of the emission, including the properties and nature of the flares. Particularly useful for meteoritics is the study by Wolk et al. (2005) of $\sim 30$ COUP stars with masses close to solar. This work tells us that the young sun was luminous in X-rays, emitted many hard photons with energies greater than 1 keV, and was susceptible to frequent strong flares. The young Sun was extraordinarily luminous in X-rays, emitting $\sim 10^{30}$ erg s$^{-1}$ continuously and flares with peak luminosities sometimes reaching $\sim 10^{31} - 10^{32}$ erg s$^{-1}$. The contemporary Sun, in comparison, typically emits $\sim 10^{26} - 10^{27}$ erg s$^{-1}$ in the CHANDRA band with occasional flares peaking up to $\sim 3 \times 10^{28}$ erg s$^{-1}$. Furthermore, the spectrum of the young Sun was harder, emitting many photons with energies in the 1 − 10 keV range.

The X-rays emitted from YSOs can affect all of the near dynamical components that are involved in the formation of low-mass stars: the accretion disk, the outflowing wind or winds, the accretion funnel that actually builds the star,

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$^5$The X-ray properties of stars at an earlier stage of evolution lying deeper inside the Orion molecular cloud have been studied by Grosso et al. (2005).
and the magnetically active regions interior to the inner edge of the accretion disk where magnetic reconnection, particle acceleration, and spallation reactions occur. The X-rays help determine the physical and chemical properties of these regions, and also offer interesting new diagnostic opportunities for measuring their properties. Particularly interesting is the possibility that, by determining the level of midplane ionization important for the MRI, the X-rays affect the accretion that builds the young star. Equally intriguing is the potential role of the dead zone, associated with layered accretion, in the formation of planets. Perhaps most important, the characteristic properties of the X-rays from sun-like stars provide a foundation for the local irradiation model for the production of the short-lived radionuclides seen in chondritic meteorites. These considerations on X-ray interactions offer considerable promise for the further study of YSO X-rays and their effects.

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Figure 3. X-ray light curves for two COUP sources showing several types of flares. The second flare for source #1259 (bottom) has a peak luminosity of $0.1L_\odot$, one of the most powerful ever observed from a YSO.
Figure 4. Hard X-ray spectrum of a COUP source with a 6.4 keV feature indicative of scattering by a circumstellar disk (Tsujimoto et al. 2005, as discussed in §2.2). The crosses are the data. A best-fit model is represented by solid steps and Gaussian line components by dashed steps. The 6.4 keV (low-ionization Fe) and 6.7 keV (high ionization Fe) features are indicated by solid and broken arrows, respectively.

Figure 5. Temperature profiles from GNI04 for the surface of the protoplanetary disk atmosphere discussed in §3.1 of the text. The radial distance is 1 AU, and the mass-loss rate is $10^{-8} M_\odot$ yr$^{-1}$. The dashed line is the dust temperature of D’Alessio et al. (1999). The solid curves are gas temperature profiles labeled by the coefficient $\alpha$ in Eq. 2. The choice $\alpha = 0.01$ closely follows the limiting case of pure X-ray heating. The abscissa is vertical column density in cm$^{-2}$, and the ordinate is temperature in degrees K.