EFFECTS OF ENERGETIC RADIATION IN YOUNG STELLAR OBJECTS

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Astronomical observations provide compelling evidence for enhanced magnetic activity in T Tauri stars and some protostars in the form of strong X-ray and nonthermal radio emission. A typical value for the X-ray luminosity of a low-mass young stellar object (YSO) is in the range $L_X \sim 10^{28} - 10^{30}$ erg s^{-1} or $L_X/L_{bol} \sim 10^{-4}$, but L_X can increase by orders of magnitude during a flare. Irradiation at such power levels can have important effects on the physical and chemical properties of surrounding material. We discuss in detail the X-ray ionization of circumstellar accretion disks and cloud cores, where X-rays can dominate other ionization sources out to $\gtrsim 0.01$ pc = 2000 AU. The X-rays can also induce a wide variety of changes in the chemical and physical properties of the environment and may promote MHD turbulence and accretion in disks. Radio emission from MeV electrons implies that energetic particles are also produced by YSOs, and a variety of meteoritic measurements support their presence.

I. INTRODUCTION

The formation and early evolutionary stages of low-mass (solar-like) stars and their disks are usually viewed from the perspective of low-temperature astronomy. Observational evidence for gravitational collapse of molecular gas is found through millimeter lines; dust in the circumstellar disks of pre-main sequence stars is studied through continuum emission at infrared through millimeter wavelengths; and jets and bipolar outflows are seen in optical through millimeter emission lines and thermal radio continuum emission. The stages of YSO evolution are frequently classified by their infrared spectra: Class 0 protostars are in their youngest infalling phase; Class I protostars and Class II classical T Tauri stars are dominated by star-disk interactions;

and Class III weak-lined T Tauri stars have little or no disk material (Lada 1991, André and Montmerle 1994).

There is extensive observational evidence that high energy processes coexist with cold material in young stellar objects. Variable keV X-ray emission with $L_X \sim 10^{-4} - 10^{-3}\,L_{\rm bol}$ is nearly ubiquitous in Class II and Class III YSOs (T Tauri stars), and is detected at similar or higher levels in several Class I protostars. This emission requires the presence of a large volume of high density plasma at a temperature of about 10^7 K. The plasma must be magnetically confined, probably in large loops on a scale $> R_\star$. Nonthermal centimeter radio continuum emission is seen in several dozen YSOs at levels 3 to 6 orders of magnitude higher than in the contemporary Sun. A comprehensive review of over 200 optical, X-ray, and radio studies of magnetic activity and associated high energy processes is given by Feigelson and Montmerle (1999).

The key to the puzzle of the coexistence of keV$-$MeV radiation with much colder matter ($\leq$eV-particles) is the presence of dynamic magnetic fields that lead to violent reconnection phenomena. The physical context is analogous to the outer layers of the Sun, where magnetic fields generated in the solar interior are stirred by sub-photospheric motions until reconnection produces flares which heat trapped gas to X-ray temperatures and accelerate particles to MeV-GeV energies via shocks and plasma processes. But the YSO situation is considerably more complex (and uncertain) than the contemporary Sun. YSO magnetic fields may be produced by a dynamo or may be inherited from the parent molecular cloud. Magnetic field footprints may lodge in the star, connect the star to the disk, or link portions of the disk.

Our goal in this paper is to discuss some of the consequences of high-energy processes for the gas and dust in the circumstellar envelopes and disks of mainly low-mass YSOs. X-rays will ionize the gas and promote gas-field coupling, alter the solids in dust particles, and induce chemical reactions. Energetic flare particles will initiate nuclear reactions with the nuclei of disk atoms, and flare shocks will affect disk material in complex ways. Many of these effects have yet to be examined in depth. After summarizing the astronomical observations of YSO X-rays, we will concentrate on the ionization effects of X-rays on the gaseous parts of the circumstellar environment, the subject of recent theoretical studies. We then discuss X-ray induced chemistry, irradiation of dust, and links to meteoritics.

II. ASTRONOMICAL OBSERVATIONS

The first evidence for extremely hot plasma in YSOs was detected in the Orion Trapezium as early as 1972 with the UHURU satellite, although the understanding that the source was hundreds of individual low mass stars only emerged with the Einstein, ROSAT and ASCA imaging X-ray telescopes of the 1980−90's. All major nearby sites of star formation have now been studied in the X-ray band, including the Taurus-Auriga, Ophiuchus, Chamaeleon, Corona Australis, and Perseus clouds, portions of the Sco-Cen and Orion associations, as well as the more distant Rosette and Monoceros molecular clouds (e.g. Feigelson et al. 1993; Strom and Strom 1994; Gagné et al. 1995; Casanova et al. 1995; Preibisch et al. 1996; Preibisch 1997; Neuhäuser 1887; Gregorio-Hetem et al. 1998).

Figure 1 is an example of the central portion of a cluster of low-mass YSOs observed in X-rays by ROSAT. It is typical of X-ray images of star-forming molecular clouds, which show dozens of faint variable sources associated with an optical and/or infrared YSO. Many of the X-ray sources are previously unnoticed, optically-visible weak-lined T Tauri stars (WTT stars, e.g., Walter et al. 1988), also known as Class III YSOs from their infrared properties (Lada 1991). Optically, they are spectral type G-K-M stars lying on Hayashi tracks above the main sequence in the Hertzsprung-Russell diagram. They are characterized by little or no infrared excess, strong Li $\lambda\,6707$ absorption lines, large cool starspots, strong chromospheric absorption and weak Hα emission lines. Their soft X-ray luminosities (energies $\sim$ 0.2-2 keV) are typically in the range 10^{28} - 10^{30} erg s^{-1}, or factors of $10^2 - 10^3$ above contemporary solar levels.

Virtually all of these X-ray sources vary on time scales of hours to days. Some show slow aperiodic variation with amplitude variations of a factor ≤ 2 but at any moment several percent of the sources exhibit high-amplitude rapid flares with peak $L_{\rm X} \simeq 10^{30} - 10^{32}$ erg s^{-1}. One YSO is known with quiescent emission of $L_{\rm X} \simeq 2 \times 10^{32}$ erg s^{-1} (Preibisch et al. 1998). A typical flare lasts one to several hours, with a fast rise and a slow decay. The particular flare illustrated in Fig. 2 had a somewhat shorter decay time than usual and is reminiscent of the common impulsive flares seen in the Sun. Modeling the X-ray spectrum requires a multi-temperature plasma with temperatures around 2−20 MK during low states to roughly 60 MK for stronger sources and flares (e.g., Skinner et al. 1997; Preibisch et al. 1998).

A large fraction of classical T Tauri stars (CTT stars, or Class II YSOs) are detected with X-ray characteristics that are very similar to Class III stars. This may indicate that the presence (in Class II) or absence (in Class III) of a disk is not critical to X-ray production or absorption, and that the magnetic footprints lie on the stellar surface (Feigelson et al. 1991). However, simple astrophysical modeling of the radiative cooling of the $10^{30} - 10^{31}$ erg s^{-1} X-ray flares in Class II stars consistently indicates loop sizes of order 10^{11} cm, much larger than the $10^9 - 10^{10}$ cm loops seen on the Sun, and sometimes larger than the X-ray emitting star itself. Field lines linking the star and disk at the corotation radius may explain the strongest of these powerful flares, if not X-ray flares in general (Hayashi et al. 1996; Shu et al. 1997).

Recent observations have detected X-ray emission from several Class I protostars with estimated ages $\approx 10^5$ yr (Casanova et al. 1995; Koyama et al. 1996; Grosso et al. 1997). The detected Class I YSOs tend to have harder spectra than T Tauri stars, and their flare luminosities can be considerably higher, in the range $L_X \simeq 10^{30}$ to $> 10^{33}$ erg s^{-1}. However, the detected protostars probably represent the top of the protostellar luminosity function, since many other Class I sources have not been detected at these levels (Carkner et al. 1998).

Another important observational indicator of high energy magnetic activity in YSO systems is the detection of nonthermal radio continuum emission in several dozen Class III stars (see the review by André 1996). Surveys with the NRAO Very Large Array indicate that roughly 20% of weak-lined T Tauri stars have radio luminosity densities $L_r(8\,\mathrm{GHz}) \geq 10^{15.5}$ erg s^{-1} Hz^{-1} (Chiang et al. 1996). This is ~ 2 orders of magnitude above the most active late-type main sequence stars, and many orders of magnitude above contemporary solar levels. The radio emission is often variable and, in a few cases, circularly polarized (e.g. White et al. 1992). This shows that the emission is gyrosynchrotron radiation from mildly relativistic electrons spiraling in well-ordered magnetic fields. The same mechanism is present in other magnetically active late-type stars like dMe flare stars, RS CVn binaries, and the Sun.

Nonthermal radio emission has not yet been detected in Class II YSOs, arguably because emission from magnetic loops near the star suffers free-free absorption by the partially ionized outflows of CTT stars (André 1996). Class I stars frequently show extended free-free emission from the base of their bipolar outflows (see the review by Rodríguez 1997). Two protostars do exhibit circularly-polarized, variable emission denoting gyrosynchrotron emission: T Tauri South is resolved into two lobes of opposite helicity, suggesting particle acceleration in the outflow (Ray et al. 1997), while CrA IRS 5 exhibits rapid polarized flaring indicative of magnetic reconnection events near the star (Feigelson et al. 1998).

Optical studies have recently confirmed the presence of strong magnetic fields on the surfaces of Class III and some Class II YSOs. Zeeman effect measurements show surface fields in several stars with $Bf \simeq 1 - 3\,\mathrm{kG}$, where f is the surface filling factor (Johns-Krull et al. 1998; Guenther et al. 1998). Periodic photometric variations and Doppler imaging studies reveal rotationally-modulated, cool starspots covering up to half of the stellar surface (e.g., Bouvier et al. 1995; Hatzes et al. 1997).

It appears likely that *all* low-mass YSOs possess strong magnetic fields near the stellar surface that extend out to the circumstellar disk.

These fields may be the sites of powerful magnetic reconnection events that produce ionizing X-rays and accelerate electrons to MeV energies. Reconnection of large field structures is a natural consequence of theories of low-mass star formation, where stellar field lines are linked to the disk and collimate both inflows and outflows (see the chapters by Shu et al. and by Königl and Pudritz). In view of the numerous qualitative similarities between X-ray and radio emission mechanisms in YSOs and in the Sun, it is also reasonable to infer that YSO flares produce MeV protons and heavier ions, analogous to solar flare cosmic rays.

III. X-RAY INTERACTION PHYSICS

The principal effects of X-rays on the cold interstellar medium (ISM) are ionization, excitation, and heating. The ionization can help couple the gas and ambient magnetic fields. It may also induce a characteristic X-ray photochemistry and alter the properties of dust. Early research on these issues dates back to the beginning of X-ray astronomy (see the review by Dalgarno and McCray 1972). Soft X-rays and low-energy cosmic rays were then considered the most promising ionization sources for interstellar clouds shielded from the interstellar far-UV starlight. While the underlying ionization mechanism is due to electronic collisions in both cases, X-rays are absorbed by much smaller columns of matter than cosmic rays. Thus galactic cosmic rays are able to provide a more global, low-level ionization of the ISM, whereas X-rays can produce a high level of localized ionization. A stellar X-ray source in a molecular environment is surrounded first by ionized and then by atomic and molecular material (e.g., Halpern and Grindlay 1980; Lepp and McCray 1983). Lepp et al. (1985) showed that X-irradiated interstellar gas can, under certain conditions, occur in three stable phases: coronal gas ($T > 10^5$ K), warm gas ($T \approx 10^4$ K), and cold gas ($T < 10^2$ K) which can become molecular. The molecular phase has not yet been fully studied, and X-ray induced chemistry is a subject of renewed interest (e.g., Maloney et al. 1996; Lepp and Dalgarno 1996; Yan and Dalgarno 1997), as discussed in §VI.

An intriguing early suggestion was that X-rays play a role in regulating the rate of star formation through the inhibition of gravitational collapse by the suppression of ambipolar diffusion in an X-ray ionized medium (Silk and Norman 1983). However, we will see below that stellar X-ray ionization is generally not effective for the bulk of a molecular cloud core (≥ 0.1 pc). The present consensus is that galactic far-UV and cosmic rays are more important than X-rays for coupling magnetic fields and interstellar cloud material on this spatial scale (McKee 1989). However, X-rays can influence other steps in early stellar evolution on scales < 0.1 pc, such as infall, accretion, and outflow.

The photoelectric effect is the most important interaction for X-rays in the 1–10 keV energy range relevant for YSOs. Most of the X-rays (> 80% above 1 keV) are absorbed by low-abundance elements heavier than H and He. If the irradiated matter is only weakly ionized, the primary photoelectron ejected from a heavy element, which typically has an energy $\sim$ keV, is able to collisionally ionize and excite many H and He atoms (and H_2 molecules in a molecular region), generating lower-energy secondary electrons which produce further ionization. The role of secondary electrons in X-ray ionization and heating was first considered for atomic regions by Silk and Werner (1969).

X-rays and cosmic rays ionize interstellar and circumstellar gas in different ways. Cosmic rays primarily eject outer-shell electrons and thus affect light and heavy atoms in much the same fashion. Most cosmic-ray ionization comes from abundant H and He atoms. In contrast, X-rays are absorbed more strongly by heavy atoms, from which they eject K- and L-shell electrons. This is accompanied by the Auger effect, in which the de-excitation of an atom with $Z > 3$ is accompanied by the ejection of several electrons after an internal cascade. The mean number of Auger electrons ($\mathcal{A}$) increases with Z from $\mathcal{A} = 1$ for $Z \leq 10$ (Ne) to $\mathcal{A} = 4.75$ for Fe (Kaastra and Mewe 1993). The primary fast X-ray photoelectron also produces additional ionization of atoms and molecules. The mean energy to make an ion pair in weakly-ionized, cosmic-abundance gas is $\Delta\epsilon \approx 35\,\mathrm{eV}$. About 40% of this energy goes into ionization, 45% into excitation, and 15% into heat for an electron fraction $x_{\mathrm{e}} = 10^{-4}$ in an atomic gas (Shull and Van Steenberg 1985). Thus 1 keV of incident X-ray energy produces a cascade of $\mathcal{S} \approx 1000/35 \approx 30$ secondary electrons, and the number of secondary electrons $\mathcal{S}$ is generally much greater than $\mathcal{A}$, the number of Auger electrons. The energy of the Auger electrons may be high ($\sim$ keV) if they come from the lower atomic levels, but more often they come from higher levels and emerge with comparatively low energy. In practice, their effects have usually been ignored.

A valuable source of X-ray absorption cross sections is the tabulation of Henke et al. (1993), updated and available on-line at www-cxro.lbl.gov/optical_constants/asf.html. It is only slightly changed from the earlier edition used by Morrison and McCammon (1983). The absorption cross section is usually expressed as the total photoelectric cross section per H nucleus, $\sigma(E) = \sum_k x_k \; \sigma_k(E)$, which is a sum over the elemental cross sections $\sigma_k(E)$ weighted by the abundances x_k of each atomic species. A typical photoelectric cross section has a K-shell ionization threshold, then decreases approximately as E^{-3}, so that the sum displays a discontinuity when a new elemental ionization threshold energy is reached. $\sigma(E)$ is fairly independent of the depletion of many heavy elements onto grains, as long as the grains are not too large (Fireman 1974; Morrison and McCammon 1983).

The total photoelectric cross section decreases rapidly with X-ray energy E and, after smoothing, can be fitted by a power law

$$\sigma(E) = \tilde{\sigma}\ (E/\mathrm{keV})^{-n}. \tag{1}$$

For cosmic abundances, normal gas-to-dust ratio, and X-ray energies 1-20 keV, the fit coefficients are $\tilde{\sigma} = 2.27 \times 10^{-22}\,\mathrm{cm}^2$ and $n = 2.485$ (Glassgold et al. 1997). The corresponding optical depth for absorption of an X-ray is $\tau(E) = \left(N_\mathrm{H}/10^{22}\mathrm{cm}^{-2}\right)\ \tilde{\sigma}\ (E/\mathrm{keV})^{-n}$. For $E = 1\,\mathrm{keV}$ and solar abundances, this becomes $\tau(1\,\mathrm{keV}) = N_\mathrm{H}/4.41 \times 10^{21}\mathrm{cm}^{-2}$. If the usual conversion between N_H and A_V for diffuse interstellar clouds is used, then $\tau(1\,\mathrm{keV}) = 1$ occurs when $A_V \simeq 2$.

Two additional effects can be important. First, X-rays above $E \sim 2\,\mathrm{keV}$ can also ionize when they scatter through a large angle (e.g., Halpern and Grindlay 1980). For the energy range of interest, the process is essentially Thomson scattering although it is conventionally referred to as Compton ionization. The Compton ionized electron acquires only a small amount of energy, $\sim E^2/(m_\mathrm{e}c^2)$, not enough to make any secondaries until $E \sim 100\,\mathrm{keV}$. The energy transfer is much smaller than in the photoelectric effect, especially for the heavy atoms responsible for most of the absorption cross section, and Compton energy losses do not become competitive until $E \sim 20\,\mathrm{keV}$. The second effect is that some of the energy absorbed by high-Z atoms goes into fluorescence instead of the primary and Auger electrons. The fluorescent yield increases with Z and reaches about 35% for Fe. However, much of the fluorescent energy still goes into the production of secondary electrons because the fluorescence occurs mainly at X-ray energies. A reasonably accurate calculation of the ionization and heating of cool interstellar or circumstellar matter by YSO X-rays can be made by assuming that all of the X-ray energy goes into secondary electron production, with a small correction for heating. However, important X-ray diagnostics are contained in the fluorescent radiation at longer wavelengths (e.g., Shapiro and Bahcall 1981; Lepp and McCray 1983).

IV. X-RAY IONIZATION OF THE ENVIRONMENT

YSO X-rays can partially ionize nearby circumstellar and interstellar matter through the processes just described. We can estimate the distance from the YSO within which X-ray ionization will dominate that produced by galactic cosmic rays. Following Krolik and Kallman (1983), we write the secondary electron contribution to the ionization rate at a distance r from a stellar X-ray source of luminosity L_X, temperature kT_X, and low-energy cut-off E_o, as

$$\zeta_\mathrm{X} = \left[\left(L_\mathrm{X}/kT_\mathrm{X}4\pi r^2\right)\sigma(kT_\mathrm{X})\right]\left(kT_\mathrm{X}/\Delta\epsilon\right)\ J(\tau, x_o). \tag{2}$$

In this equation, $\sigma(kT_\mathrm{X})$ is the total photoelectric absorption cross section in Eq. (1) evaluated at $E = kT_\mathrm{X}$; $\Delta\epsilon$ is the energy to make an ion pair; and $J(\tau, x_o)$ is an attenuation factor (called J_h by Krolik and Kallman 1983) that depends on $\tau = \tau(kT_{\rm X})$ and $x_o = E_o/kT_{\rm X}$:

$$J(\tau, x_o) = \int_{x_o}^{\infty} dx\, x^{-n}\, e^{-(x+\tau\, x^{-n})}. \qquad (3)$$

The x^{-n} factors come from the cross section fit in Eq. (1), and the other exponential comes from the thermal bremsstrahlung spectrum.

The factors in Eq. (2) can be understood as follows. The first (between square brackets) is the primary ionization rate, assuming that all of the photons contribute the same as the one with the mean energy, $E = kT_{\rm X}$. The next factor is the mean number of secondary electrons produced by each primary photoelectron, $(kT_{\rm X}/\Delta\epsilon)$. Note that the last factor, the attenuation factor J, is not unity at zero optical depth, i.e., $J(0, x_o) \equiv J_o \neq 1$. When $x_o \ll 1$, $J_o \approx 1/(n-1)x_o^{n-1} \gg 1$ but J_o may be < 1 in the likely situation that x_o is a finite fraction of $kT_{\rm X}$.

To estimate the maximum range of X-ray interactions, we need the ionization rate at zero optical depth at a distance r from a source of X-ray luminosity $L_{29} = L_{\rm X}/(10^{29}{\rm erg\ s^{-1}})$:

$$\zeta_{\rm X} = 1.4 \times 10^{-10}\,{\rm s^{-1}}\ [\sigma(kT_{\rm X})/\sigma(1\,{\rm keV})]\ L_{29}\, J_o\,(r/{\rm AU})^{-2}. \qquad (4)$$

The total ionization rate due to external sources is the sum of contributions from X-rays, cosmic-rays, and UV radiation. Each of these is attenuated by characteristic processes that depend on the properties of the medium; we have already discussed the physics of X-ray absorption. Low-energy cosmic-rays may be partially excluded from dense regions by magnetic scattering (Skilling and Strong 1976; Cesarsky and Völk 1978), especially if stellar winds are present (Parker 1960). Many attempts have been made to determine the effective cosmic-ray ionization rate in UV-shielded clouds, e.g., by chemical modeling of molecular line observations (see the review by Lepp 1992), but this important parameter is still not known to within better than an order of magnitude. This difficulty is exemplified by two recent analyses of ionization in molecular cloud cores: one group concludes that the ionization rates may differ between cores by $1-2$ orders of magnitude (Caselli et al. 1998), while another group concludes that the ionization rates are essentially the same (Williams et al. 1998).

We express the cosmic-ray ionization rate in UV-shielded cores as $\zeta_{\rm CR} = \zeta_{-17} \times 10^{-17}\,{\rm s^{-1}}$, and use Eq. (4) to define the distance where X-ray and cosmic-ray ionization become equal,

$$r_{\rm max} \approx 0.02\,{\rm pc}\ [(\sigma(kT_{\rm X})/\sigma(1\,{\rm keV}))\ L_{29}\, J_o/\zeta_{-17}]^{1/2}. \qquad (5)$$

T Tauri stars have typical temperatures $kT_{\rm X} = 1\,{\rm keV}$ and X-ray luminosities in the range $L_{29} = 0.1 - 100$ (see §II). Taking into account variations in YSO X-ray properties and the uncertainty in ζ_{-17}, the overall range in $r_{\max}$ is about a factor of 100. For a typical YSO, X-ray ionization dominates cosmic ray ionization out to $\simeq 1000$ AU. For the more luminous X-ray sources, it may dominate the ionization over much of the cloud core shielded from interstellar UV radiation, especially if they are grouped in clusters with inter-star distances $d_\star \sim$ a few 0.01 pc. In the dense ρ Ophiuchi cloud Core F region, where $d_\star$ is small, Carkner (1998) finds that $\zeta_X > \zeta_{-17}$ over several percent of the cloud volume.

For considerations of ionization, the effective L_X for a given YSO may be closer to the peak luminosity of occasional powerful flares, rather than the time-averaged luminosity. The recombination coefficient for a molecular gas is $\beta \approx 10^{-7}\mathrm{cm}^3\mathrm{s}^{-1}$, so that regions with $n_\mathrm{H} = 10^4\,\mathrm{cm}^{-3}$ and $x_\mathrm{e} < 10^{-6}$ will recombine on a time-scale > 30 yr. This time scale is larger than the duty cycle of flares which, although poorly known, is measured in days to months (Montmerle et al. 1983). A YSO may thus have an X-ray dominated ionization region that is considerably larger than $0.01\,\mathrm{pc} = 2000\,\mathrm{AU}$, which would encompass nearby protostellar cores.

Similar considerations should apply to the environs of the most X-ray luminous low-mass YSOs (Preibisch 1998) and intermediate-mass YSOs such as Herbig Ae/Be stars and ZAMS B stars, for which $L_X \simeq 10^{30} - 10^{32}$ erg s^{-1} (Caillault and Zoonematkermani 1989; Zinnecker and Preibisch 1994). Although B stars are more luminous in UV than X-rays, the UV is absorbed much closer to the star. Hard X-rays from W3 have recently been observed by ASCA (Hofner & Churchwell 1997) and may produce substantial environmental effects in this region. The variable X-ray emission from θ^1 Orionis has recently been shown by Gagné et al. (1997) to be periodic on the same time scale as other spectral lines (15 days). Babel & Montmerle (1997a,b) have been able to account for the observations within the framework of a magnetically-confined wind.

While $r_{\max}$ gives a rough estimate of the maximum extent of X-ray ionization, the detailed effects of YSO X-rays depend on the attenuation factor J in Eq. (2). Glassgold et al. (1997, henceforth GNI) show that, on ignoring the effects of the low-energy cutoff, J is well approximated for all relevant values of τ (even $\tau \ll 1$) by an asymptotic expansion of the integral in Eq. (3),

$$J = A\tau^{-a}\, e^{-B\tau^b}, \tag{6}$$

where a, A, B and b are fit parameters that depend on abundances and the energy band under consideration. For solar abundances and energies around 1 keV ($n = 2.485$), $A = 0.800$, $a = 0.570$, $B = 1.821$, and $b = 0.287$.

Returning to Eq. (3), we see that (since $n > 1$) J becomes singular at $\tau = 0$ for $E_o = 0$, which is unphysical because the photoelectric effect requires a minimum energy, such as 13.6 eV to ionize H. More importantly, soft X-rays are likely to be absorbed near the source. Thus the low-energy cutoff E_o included in Eqs. (2) and (3) must be at least as large as 0.0136 keV and surely much larger for directions which intersect major mass components of the YSO. We are assured by the detection of X-rays from most YSOs that E_o is not so high that all X-rays are absorbed very close to the star. When the line of sight absorption to a YSO can be measured with optical-infrared photometry, the result usually agrees with E_o determined from X-ray spectra. Nonetheless, it is likely that E_o varies with direction for a given YSO due to the asymmetries associated with the accretion disk and with the inflows and outflows.

Figure 3 shows how the ionization rate depends on the optical depth, $\tau(1\,\mathrm{keV})$. All of the curves are calculated numerically for $E_o = 1\,\mathrm{keV}$, except the one with solid triangles, which is based on Eq. (3) without a low-energy cutoff. The dotted line is an exact calculation (with no cutoff) to show the accuracy of the asymptotic calculation. The solid curves for $kT_{\rm X} = 1$ and $5\,\mathrm{keV}$ photons become flat below $\tau = 1$ due to the cutoff. The curve for $kT_{\rm X} = 1\,\mathrm{keV}$ is only about 40% higher in this region than the curve for $kT_{\rm X} = 5\,\mathrm{keV}$, despite the fact that the cross section is 55 times larger than at the higher energy, because the 1-keV cutoff applied to a $kT_{\rm X} = 1\,\mathrm{keV}$ spectrum removes most of the photons. Figure 3 also shows the greater penetrability of the high-energy photons at large optical depths, leading to ionization rates for $kT_{\rm X} = 5\,\mathrm{keV}$ that are more than a factor of 100 larger than for $kT_{\rm X} = 1\,\mathrm{keV}$.

V. X-RAY EFFECTS ON CIRCUMSTELLAR DISKS

Complex patterns of infall, accretion, and outflow are present in YSOs at distances where X-ray ionization may play an role. We concentrate on the accretion disk where the results have been most fully developed. This problem has potential importance for understanding the currently unknown origin of YSO accretion disk viscosity. The viscosity may have an magnetohydrodynamic origin of the type advocated by Balbus and Hawley (1991), who proposed that differential rotation drives the perpendicular magnetic field of an accretion disk unstable. If well-coupled to the largely neutral disk material, this "magnetorotational" instability then makes the disk turbulent. X-ray irradiation of the disk is important because the X-rays can supply the ionization needed to couple the magnetic field to the the neutral disk material.

Gammie (1996) addressed the possible role of the Balbus-Hawley instability for YSO disk accretion assuming that galactic cosmic rays are the dominant source of ionization. Takano and his collaborators (e.g., Umebayashi and Takano 1990) had established that cosmic rays can ionize those parts of disks with mass surface column densities $\Sigma \leq 200\,\mathrm{g\,cm^{-2}}$. Since both theory and observations suggest that the inner regions of YSO accretion disk are much thicker, $\Sigma \sim 2000\,\mathrm{g\,cm^{-2}}$, Gammie concluded that only the outer layers of disks would be well-coupled to magnetic fields. A potential problem for this attractive idea is that low-energy cosmic rays are likely to be excluded from the disk by the strong magnetized winds of YSOs (Parker 1960).

GNI made the first calculations of X-ray ionization of a YSO accretion disk using Eqs. (2) and (3). They adopted the steady, minimum solar nebula disk model described by Hayashi et al. (1985), with mass density and temperature given by

$$\rho(r,z) = \rho_o (r/\mathrm{AU})^{-q} e^{-z^2/2H^2} \qquad T = T_o (r/\mathrm{AU})^{-p}, \tag{7}$$

where r and z are cylindrical coordinates. Hayashi et al. chose the power-law indices as $q = 2.75$ and $p = 0.5$, so that the mid-plane density and temperature at 1 AU are $\rho_o = 1.4 \times 10^{-9}\,\mathrm{g\ cm^{-3}}$ and $T_o = 280\,\mathrm{K}$. The vertical scale-height parameter H and surface mass density Σ are then expressed by the power laws,

$$\Sigma = \Sigma_o (r/\mathrm{AU})^{-1.5} \qquad H = H_o (r/\mathrm{AU})^{1.25}, \tag{8}$$

with $\Sigma_o = 1700\,\mathrm{g\ cm^{-2}}$ and $H_o = 5.0 \times 10^{11}\,\mathrm{cm}$ if all of the hydrogen is molecular. When integrated from $r_1 = 0.35\,\mathrm{AU}$ to $r_2 = 35\,\mathrm{AU}$, the mass of the disk is $M_\mathrm{D} = 0.013\,M_\odot$. The mid-plane volume density of hydrogen nuclei at 1 AU is $n_\mathrm{H} = 5.8 \times 10^{14}\,\mathrm{cm^{-3}}$ (using $\rho/n_\mathrm{H} = 1.425\,m_\mathrm{H}$). The values of p, T_o, and M_D are consistent with millimeter-wave measurements of YSO disks (e.g. Sargent et al. 1990; André and Montmerle 1994).

GNI assumed that the disk was geometrically thin ($H \ll r$) and planar (not flared), and that the X-ray source is elevated a height $z_\mathrm{S} = 12\,R_\odot$ above the disk midplane, as suggested by the the x-wind model (Shu et al. 1994) and roughly consistent with the large loop sizes inferred from X-ray and radio flares (§II). The X-rays then encounter the disk at a small angle $\sim z_\mathrm{S}/r$. GNI measured vertical distances with the vertical column density,

$$N_\perp(r,z) = \int_z^\infty n_\mathrm{H}(r,z')dz'. \tag{9}$$

They assumed that the dust particles had settled to the midplane of the disk, following the calculations of Cuzzi and Weidenschilling (1993), and ignored the z-dependence of temperature, which may affect the local density structure (e.g., Bell et al. 1997) and temperature-dependent reaction rates. The main result of GNI was that hard X-rays penetrate to large vertical column densities towards the disk midplane, typically at 1 AU to $N_\perp \sim 10^{24}$ and $10^{25}\,\mathrm{cm}^{-2}$ for $kT_\mathrm{X} = 1$ and 5 keV, respectively. This ionization level is sufficient to produce an electron fraction in excess of the estimated critical electron fraction needed to couple magnetic fields and disk matter (Blaes and Balbus 1994, Gammie 1996). Because only an outer layer of the disk is ionized, GNI recovered Gammie's picture of layered MHD accretion, where an interior dead zone develops at small radial distances around $r \leq 5$ AU.

A full 3-D calculation of X-ray transport and ionization in axially-symmetric disks has been developed by Igea and Glassgold (1998) using a Monte Carlo method. It is capable of treating flared disks and includes Compton scattering as well as photoelectric absorption. Figure 4 gives a typical result for the ionization rate at $r = 1\,\mathrm{AU}$ in the minimum solar nebula disk described above, irradiated by X-rays with $L_\mathrm{X} = 10^{29}\,\mathrm{erg\ s}^{-1}$. The three curves plot the ionization rate vs. $N_\perp$ for thermal spectra with $kT_\mathrm{X} = 3$, 5, and 8 keV and for a fixed low-energy cutoff of $E_o = 1\,\mathrm{keV}$. The X-ray emitting region is modeled as a ring at height $z_\mathrm{S} = 10\,R_\odot$ and radius $r_\mathrm{S} = 10\,R_\odot$. All three curves show three components: a flat portion at small $N_\perp < 10^{20}\,\mathrm{cm}^{-2}$ (or vertical heights $z > 5H_o$) where absorption is negligible; a smooth decline due to absorption for $10^{21} < N_\perp < 2 \times 10^{23}\,\mathrm{cm}^{-2}$ ($2 < z < 4.5H_o$); and a "scattering shoulder" for $N_\perp > 2 \times 10^{23}\,\mathrm{cm}^{-2}$, where the ionization rate declines less rapidly due to Compton scattering. The remarkable similarity of the curves at all optical depths depends critically on the use of the vertical column depth $N_\perp$ as the independent variable. The scaling displayed in Fig. 4 is also found at other disk radii and is insensitive to changes in disk parameters such as disk mass M_D, surface density Σ_o, and slope q. The absolute level of the ionization scales linearly with L_X and inversely with the radial distance r, i.e., as the incident flux.

These results show that, over a large range of column densities ($N_\perp < 2 \times 10^{24}\,\mathrm{cm}^{-2}$), the ionization rate is larger than the nominal value due to galactic cosmic rays, $\zeta_\mathrm{CR} = 10^{-17}\mathrm{s}^{-1}$. However, as remarked earlier, cosmic rays may not penetrate into the inner disk due to wind modulation. Dead zones are also expected to be present in the interiors of X-ray ionized disks. For example, Fig. 4 shows that the ionization rate falls precipitously for $N_\perp > 10^{25}\,\mathrm{cm}^{-2}$, whereas the half-disk thickness in this case corresponds to $N_\perp = 10^{26}\,\mathrm{cm}^{-2}$. Thus, at 1 AU, no more than the outer 10% of the disk mass can be coupled to the magnetic field. Because Σ decreases with r, the dead zone disappears at large radii, and the entire outer disk will be ionized by X-rays. Full penetration of X-rays to the midplane first occurs for the model in Fig. 4 at $r = 5\,\mathrm{AU}$. The occurrence of a dead zone can be expected to have important implications for the dynamics of YSO disk accretion

(Gammie 1996 and chapter by Stone et al., this volume). It would therefore be of great interest to include the effects of X-ray ionization in numerical MHD simulations of disk dynamics.

VI. X-RAY INDUCED CHEMISTRY

When photons from an X-ray source penetrate into a cloud, they produce a sequence of chemical zones with a wide range of physical and chemical properties that range from hot, highly-ionized to cool, lightly-ionized gas (§III). This progression can be understood in terms of the variation in the local ionization parameter, defined here as $\xi \equiv \zeta/n$. A familiar example of the use of an ionization parameter arises in calculating the electron fraction in molecular regions dominated by long-lived molecular ions such as HCO^+. In this case, the electron fraction is given approximately as $x_e = (\xi/\beta)^{1/2}$, where β is the effective dissociative recombination coefficient. The ionization parameter changes with distance into a cloud due to geometric dilution and absorption of the incident radiation by the intervening medium, which may have considerable density variation. The combined effects of the energy-dependence of the absorption cross section, Eq. (1), and the broad spectrum of the source tend to produce gradual rather than sharp phase transitions which extend over a large range of column densities. This situation may be contrasted with a conventional photo-dissociation region (produced by far-UV radiation longward of the Lyman limit), which has a narrow transition of the order of several magnitudes of visual extinction and no fully-ionized zone.

The X-ray chemistry of YSOs is a particularly challenging but largely undeveloped area of astrochemistry, primarily because account has to be taken of the special geometry and the time dependence and complex history of the flows important in star formation. However, in the absence of definitive studies of YSO X-ray chemistry, considerable insight can be gained from steady-state chemical models of interstellar clouds irradiated by X-rays (e.g., Maloney, Hollenbach, & Tielens 1996, henceforth MHT; Lepp & Dalgarno 1996; Sternberg, Yan, & Dalgarno 1997; Yan & Dalgarno 1997). This research has been largely motivated by circumnuclear clouds in active galactic nuclei. Despite the much larger X-ray luminosities, $L_X \sim 10^{44}\,\mathrm{erg\ s^{-1}}$, the large distances of the clouds from the AGN (hundreds of pcs) bring the ionization parameter into the range relevant for galactic clouds near strong X-ray sources and for molecular cloud cores irradiated by YSO X-rays. For example, Maloney et al. consider the range $\xi = 10^{-19} - 10^{-24}\,\mathrm{cm^3\ s^{-1}}$ for the case $n = 10^5\,\mathrm{cm^{-3}}$, which brackets the standard cosmic-ray ionization parameter $\xi_{CR} \sim 10^{-22}\,\mathrm{cm^3\ s^{-1}}$ for this density.

According to these studies, molecule formation occurs over a large range of ξ (or, at constant density, X-ray dilution and absorption).

Its pace quickens in a warm, partially-ionized region ($T \sim 5000\,\mathrm{K}$, $x_e \sim 0.01$) that cools and becomes more neutral with decreasing ξ, and thus also more molecular. In the warmer regions, the chemistry makes use of neutral reactions promoted by X-ray heating of the gas, whereas in cooler regions the X-rays induce molecular synthesis by ion-molecule reactions.

Each of the chemical zones of a cloud exposed to an X-ray source provides a variety of spectral-line diagnostics determined by the local physical conditions and escape probabilities. Certain fine-structure transitions provide some of the strongest lines in all regions, notably [OI] 63 μm and to a lesser extent [SII] 35 μm and [FeII] 26 μm. The [CII] 158 μm line is an important diagnostic for the cooler regions ($T \leq 100\,\mathrm{K}$). The ro-vibrational transitions of H_2 are also emitted strongly by the warm parts of the X-ray transition region (Gredel and Dalgarno 1995; Tiné et al. 1997). Of special interest are molecular ions produced by secondary electrons, such as HeH^+ (Roberge and Dalgarno 1982) and H_3^+ (Draine and Woods 1991). MHT show that the 149 μm rotational transition of HeH^+ should be emitted strongly from the warm parts of an X-ray irradiated cloud, and that the 4.35 μm line of H_3^+ is quite weak. Searches for some of these infrared lines are underway using the SWS instrument on the Infrared Space Observatory (ISO) around YSOs (Montmerle et al., in preparation) and around strong X-ray sources near the center of the Milky Way (Maloney et al. 1997).

The millimeter rotational transitions of molecules and radicals provide additional chemical diagnostics in regions near YSO X-ray sources. Phillips and Lazio (1995) observed that the HCO^+ emission near the galactic center X-ray source 1E 1740.7-2942 is peaked away from the source, and suggested that this is due to enhanced destruction by X-rays. Lepp and Dalgarno (1996) and Yan and Dalgarno (1997) calculate that the primary destruction mechanism for HCO^+ is dissociative recombination with electrons. They also indicate that radicals like OH, CH, CN, and NO may provide additional evidence of X-ray induced chemistry, as suggested earlier by Krolik and Kallman (1983).

Very Long Baseline Array measurements of water masers at 22 GHz have become a powerful tool for understanding the activity at the centers of external galaxies. A beautiful example is NGC 4258, where the observations provide compelling evidence for a sub-pc Kelperian disk and a central blackhole (e.g., Miyoshi et al. 1994; Greenhill et al. 1995). The masers are believed to be located in the transition region between the atomic and molecular phases in a circumnuclear disk heated by X-rays from the central AGN (Neufeld, Maloney, & Conger 1994; Neufeld & Maloney 1995).

One difficulty in demonstrating the presence of X-ray induced chemistry is that the suggested diagnostics are often ambiguous. The most obvious source of confusion is cosmic rays, which produce chemically active secondary electrons in much the same way as X-rays. Similarly, any external energy source that heats the gas to several thousand K will initiate a neutral chemistry that is characteristic of that temperature and not of any specific heating agency. One sure solution to this problem is spectroscopic observations at high spatial resolution, because cosmic rays, X-rays, UV, and shocks all operate on different spatial scales. The HCO^+ observations of 1E 1740.7-2942 (Phillips and Lazio 1995) provide a good illustration of this point, and also call for higher spatial resolution mapping of this source.

It has long been recognized that observations of DCO^+ as well as the isotopes of HCO^+ can be used to estimate electron fractions in molecular clouds (e.g., Guélin et al. 1982; Wootten et al. 1982; Caselli et al. 1998; Williams et al. 1998). It would be of great interest to search for spatial gradients of these species in the vicinity of YSO X-ray sources. The spatial scale of ~ 0.02 pc in Eq. (5) corresponds to an angular resolution $\approx 30''$ for nearby star forming regions, so that existing millimeter arrays can probe regions where X-rays contribute to the ionization of cloud cores. Observational study of disk chemistry has only just begun (e.g. Dutrey et al. 1997). Highly sensitive planned arrays, such as the NRAO Millimeter Array and European Large Southern Array, should be effective for such studies.

Observational evidence for X-ray induced disk chemistry has been discussed by Kastner et al. (1997), who detected millimeter emission from CO, HCN, CN and HCO^+ around the nearby ($d \sim 50$ pc) T Tauri star TW Hya. They attribute the large CN/HCN ratio and the high HCO^+ abundance to the large X-ray luminosity of the star, noting that similar results are found in planetary nebulae illuminated by very hot central white dwarfs. The conclusion is not definitive however because comparable molecular abundances are seen in the non-X-ray emitting T Tauri stars DM Tau and GG Tau (Dutrey et al. 1997). Kastner (personal communication) is developing a clearer picture based on detailed chemical modeling.

VII. X-RAY INTERACTIONS WITH DUST

The interaction of X-rays with astrophysical solids is not yet well understood, especially for YSOs where the dust is at various stages of evolution and may experience complicated thermal and chemical processing. However, valuable insights may be acquired from the many laboratory studies of "radiation damage" of solids by X-rays (e.g. Cazaux 1997). When an X-ray interacts with a heavy atom in a solid, the first step is the same as in a gas (cf. §III): a photoelectron is ejected and the excited ion decays by the Auger process and, with lower probability, by fluorescence. The resulting photoelectron and several Auger-electrons propagate in a dense medium of heavy atoms, in contrast to the dilute interstellar gas dominated by light atoms. The range of an electron in a solid can be much smaller than the size of a grain, e.g., it is 200-300 Å at 1 keV (Dwek & Smith 1996). Thus a substantial fraction of the absorbed X-ray energy may be deposited in the grain, converted into phonons, and eventually re-radiated in the infrared. The transient heating of the grain can alter its spectroscopic features and also lead to the evaporation of the grain mantle. Electrons can escape from small grains, increase the grain charge and thus affect the sticking probability of gas-phase species.

The electron transport process is critical for understanding the physical and chemical properties of dust irradiated by X-rays. The problem is considerably more complicated than it is for gases, and it is exacerbated by our uncertainty of the structure of dust in the different astrophysical situations relevant for YSOs. The most complete work to date on the energy-deposition of X-rays in interstellar dust is by Dwek and Smith (1996). They considered a wide range of photon energies, from 10^{-2} to 10^{3} keV, and spherical grains of radius $a = 50 - 2000$ Å with silicate and carbon composition. For a given radius, essentially all of the X-ray energy is absorbed for photons below a certain energy. For example, a small grain with $a = 50$ Å absorbs all photons with energy $E < 0.1$ keV whereas a large grain with $a = 2000$ Å absorbs all photons with $E < 2$ keV. In related work, Laor & Draine (1993) examined the question of why the 10 μm silicate feature is usually absent or weak in AGN.

Voit (1991) analyzed the thermal and infrared spectral properties of X-irradiated spherical silicate and carbon grains, taking into account evaporative as well as radiative cooling. Very small grains are the carriers of the ubiquitous "unidentified infrared" (UIR) bands in the $3-13$ μm diffuse emission of interstellar gas, and are widely believed to be large carbonaceous molecular compounds, either polycyclic aromatic hydrocarbons (PAHs) containing 100-1000 C atoms (Boulanger et al. 1998), or kerogens (i.e., coals, composites of PAHs and aliphatic hydrocarbons with impurities like O, N or S; Papoular et al. 1996). Voit (1992) concluded that grains with $a < 10$ Å evaporate completely, which may explain the rarity of the $3 - 13$ μm UIR features in the spectra of active galactic nuclei. Vaporization of very small grains may also occur in the vicinity of X-ray emitting YSOs, and the expected weakening of the UIR features is currently being searched for in the ρ Oph cloud and in the circumstellar material of Herbig Ae/Be stars with ISO (Corcoran and Montmerle 1997).

Pursuing a promising new direction of research, Gougeon (1998) has exposed a wide variety of materials to the > 5 keV beam of the European Synchrotron Radiation Facility in Grenoble, including graphite, PAHs, coal, SiC, SiO_2, and olivine. The experimental radiation dose corresponds roughly to that obtained at 0.1 pc from a TTS having $L_X \sim 10^{30}$ erg s^{-1} for a period of 10^8 yr. A wide variety of effects are found, which still have to understood in astrophysical terms. The results for PAHs are particularly interesting, showing dehydrogenation and/or breakage of aromatic rings with consequent changes in the infrared spectra. Other materials like silicates are relatively unaffected by X-irradiation. Thus specific signatures of X-ray irradiated grains may exist and be sought with planned observatories like the Shuttle Infrared Telescope Facility.

The interaction of X-rays with dust has many chemical implications which have yet to be investigated in detail. A central issue is grain charging, which may affect gas-dust interactions and the coupling of dust to the magnetic field. The evaporation of grain mantles by X-ray irradiated grains is a potentially important desorption mechanism. Léger et al. (1985) invoked heavy cosmic rays as a way of solving the longstanding problem of the rapid condensation of molecules onto cold, interstellar grain surfaces. Bergin et al. (personal communication) have recently generalized this theory to treat the molecule-depletion problem in proto-planetary disks exposed to YSO X-rays. In order to be effective at the level suggested by observations of CO in the outer parts of accretion disks, they invoke "spot heating" to achieve grain temperatures high enough to efficiently remove CO molecules. Because disk grains are likely to be fluffy coagulates, localized regions of the grain may be heated sufficiently to cause efficient desorption.

VIII. IRRADIATION OF THE EARLY SOLAR SYSTEM

The observations summarized in §II show that YSOs, starting with Class I objects and extending in evolution all the way through the zero-age main sequence, have high levels of magnetic activity. This conclusion is not restricted to a small subsample of YSOs but appears to be a universal property of stars in the process of formation. Independent of evolutionary stage, YSOs undergo huge flares that are much more powerful than those in the contemporary Sun. The detection of extremely high levels of gyrosynchrotron emission is particularly important in this connection because it directly reveals *in situ* particle acceleration up to MeV energies in flares. It is thus reasonable to suppose that the solar nebula was subject to intense fluxes of keV X-rays, MeV particles, and shocks produced by violent magnetic reconnection events. Possible consequences include chondrule melting (Feigelson 1982; Levy and Araki 1989; Cameron 1995), correlated particle track and spallogenic ^{21}Ne excesses in some meteoritic grains (Woolum and Hohenberg 1993; Rao et al. 1997), and the production of short-lived isotopic anomalies seen in meteoritic inclusions.

The evidence for ^{41}Ca, ^{26}Al, ^{53}Mn, and other short-lived nuclides in components of primitive meteorites requires high energy processes in or near the solar nebula. Nucleosynthesis by solar energetic particles was first discussed by Fowler et al. (1962) and subsequently pursued by many others (Clayton et al. 1977; Lee 1978; Dwek 1978; Feigelson 1982; Wasserburg 1985; Clayton and Jin 1995). This "local irradiation scenario" fell out of favor partly because estimates of the particle fluence required to produce ^{26}Al by nuclear reactions in the asteroid belt were too small by several orders of magnitudes. External-seeding scenarios that posit the injection of nucleosynthetic material by a nearby supernova, asymptotic giant branch star, or Wolf-Rayet star then gained ascendency (e.g., Cameron and Truran 1977; Wasserburg 1985; Cameron 1985; Cameron 1993; Wasserburg et al. 1994; Harper 1996).

The local irradiation scenario has recently been revived in the context of the convincing astronomical evidence discussed in §II for enhanced flaring in YSOs. Shu et al. (1997) and Lee et al. (1998) use the x-wind model (e.g., Shu et al. 1994 and this volume) to locate the source of accelerated particles just inside the inner radius of the accretion disk, where magnetic reconnection is likely to occur. The reconnection events that produce the MeV electrons seen in radio continuum emission will also produce MeV particles that bombard nebular solids in the inner disk. Radioactive nuclei can then be blown out to larger radii by the x-wind (Shu et al. 1996). This model nicely solves the fluence problem by having the stellar energetic particles produce the radioactivity at several stellar radii instead of several AU. The flares may also affect the thermal properties of the ejected solids.

Lee et al. (1998) have analyzed the production of short-lived isotopes with this local irradiation model based on the x-wind model. With reasonable scalings of X-ray and particle fluxes from the current Sun to YSOs, they find that proton reactions can produce ^{41}Ca, ^{53}Mn, and ^{138}La in amounts that are consistent with measurements of meteorites. However, they are unable to obtain the high measured abundances of ^{26}Al with proton or α reactions, and instead invoke flare-generated ^{3}He nuclei using reactions such as ^{24}Mg(^{3}He,p)^{26}Al. The present, most simple form of the model cannot account for all observed isotopic anomalies, and many basic issues still need to be addressed. Goswami and Vanhala (this volume) and Jones et al. (this volume) provide a broader discussion of these issues for both the local irradiation and external seeding scenarios.

IX. CONCLUDING REMARKS

The astronomical observations summarized in §II show that low-mass YSOs, from embedded Class I protostars to Class III stars approaching the zero-age main sequence, exhibit levels of magnetic activity orders of magnitude above that seen in main sequence stars like the

Sun. YSOs undergo powerful magnetic reconnection flares that probably require organized magnetic structures larger than the star itself. Radio gyrosynchrotron emission is even more elevated than X-ray emission and directly reveals *in situ* acceleration of MeV particles within the YSO. We can thus reiterate with confidence the conclusion reached after the Einstein Observatory era: *"invoking high levels of energetic particle or radiation fluxes associated with magnetic activity in the early Sun is no longer ad hoc"* (Feigelson et al. 1991).

The most exciting observational results since the *Protostars and Planets III* review (Montmerle et al. 1993) are the detections of powerful X-ray flares in several Class I protostars and gyrosynchrotron flares in one Class I system. Further advances in this area are expected from the AXAF and XMM X-ray observatories that will be launched soon. Uncertainty remains regarding the exact location and nature of flaring within the complex magnetic fields likely to be present in YSOs. On one hand, most of the Class II and Class III phenomenology can be explained by enhanced solar-type magnetic activity; i.e., magnetic reconnection events in multi-polar fields rooted in the stellar photosphere. But a persuasive case emerges that associates flaring events, particularly in protostars, with star-disk magnetic fields in the neighborhood of the disk corotation radius. Reconnection may also occur within the disk corona and would have different implications for the effects of X-irradiation and particle bombardment of disk material.

Substantial theoretical progress has also been made since *Protostars and Planets III.* The recent calculations presented in §III−V show that disk ionization due to YSO X-rays greatly exceeds that of galactic cosmic rays. The X-rays penetrate surprisingly deep into the disk, due in part to Compton scattering. Within a few AU, the outer layers of the disk are partially ionized, and even the disk midplane is irradiated at larger radii. Thus X-ray ionization will influence the magnetohydrodynamic properties of protoplanetary disks. There are also strong indications that YSO X-rays will alter both the molecular chemistry and the solid state characteristics of cold material in the environs of YSOs (§VI−VII). In addition to the significant theoretical challenge of X-ray chemistry for YSOS, there are important opportunities for millimeter and infrared telescopes with both spectroscopic capability and high spatial resolution. Observations are needed to detect definitively the unusual molecular ions, molecular radicals, and altered grains that are expected to exist in the immediate vicinity of X-ray luminous YSOs.

Finally, it is likely that effects of magnetic flaring events that occurred when the Sun was a YSO have already been detected in ancient meteorites (§VIII). It is important to recall again that the detection of radio gyrosynchrotron emission directly demonstrates that MeV particle acceleration occurs in YSOs. Although the link between magnetic reconnection particles and meteoritics has been discussed for decades, the quantitative study of this fascinating subject has only just begun.

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FIGURE CAPTIONS

Figure 1. ROSAT image of the southern portion of the Chamaeleon I cloud showing dozens of soft X-ray sources associated with T Tauri stars (Feigelson et al. 1993)

Figure 2. ASCA light curve of flare in WTT star V 826 Tau in the L 1551 cloud (Carkner et al. 1997)

Figure 3. X-ray ionization rate vs. optical depth τ (adapted and corrected from Fig. 1 of GNI)

Figure 4. X-ray disk ionization rate in a minimum solar nebula disk (Igea and Glassgold 1998)