X-RAY IONIZATION OF PROTOSTELLAR DISKS

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Abstract. X-rays from young stellar objects can influence the physical properties of their surroundings. A particularly interesting example is the ionization of the accretion disk by hard X-rays at distances of the order of 1 AU or more. We show that X-rays induce a layered ionization structure in which the outer layer is sufficiently ionized to permit the Balbus-Hawley instability to operate and to allow accretion.

1. Introduction

Young stellar objects (YSOs) have been known to be strong emitters of X-rays since the *EINSTEIN* observatory (e.g., Ku & Chanan 1979; Feigelson & De Campli 1981; Walter & Kuhi 1981; Montmerle et al. 1983). Little has been done, however, to investigate the effects of the X-rays on the circumstellar environment, as has been emphasized by Feigelson, Montmerle, and their collaborators (e.g., Montmerle & Casanova 1995, Casanova et al. 1995). Meanwhile, new satellite observations have significantly extended the observations, especially with *ROSAT* (increased sensitivity and spatial resolution) and with *ASCA* (higher energies). Here we discuss a particular way in which X-rays from YSOs can affect their immediate environs (and the star formation process itself), which is by ionizing the nebular accretion disk.

Even before *Einstein*, theorists had begun to study how X-rays interact with the interstellar medium. In addition to investigating the microscopic

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processes involved in ionization and heating, idealized models were constructed of point sources inside isotropic clouds (e.g., Tarter et al. 1969, Tarter & Salpeter 1969). It was readily appreciated that, due to the dilution of the X-rays, the properties of the surrounding gas cloud change qualitatively with distance from the source, going from a highly ionized state close-in to a molecular region far away (e.g., Halpern & Grindlay 1980, Lepp & McCray 1983). Chemical issues were addressed by Langer (1978), Krolik & Kallman (1983) and, more recently, by Neufeld et al. (1994), Maloney et al. (1996), and Lepp & Dalgarno (1996); see the review by Sternberg et al. in this volume.

Some issues raised by the interaction of YSO X-rays with their environment were addressed more than a decade ago. Krolik & Kallman (1983) examined the penetration of X-rays at large optical depths, an issue that we return to here. Silk & Norman (1983) suggested that the X-rays from YSOs influence the rate of star formation by affecting the ionization fraction of the nascent clouds. Because the rate at which the neutrals slip away from the charged particles varies inversely with the ionization fraction, a feed-back loop may be set up that "regulates" the rate of star formation. The results to be discussed below provide an example of regulated star formation based on the ionization properties of the accretion disk.

More generally, our work is directed towards the effects of the X-rays on the immediate surroundings of a low-mass star in the process of formation. As discussed by Shu in this volume, the evolution of a rotating, magnetized protostar develops self-consistently with that of its surrounding magnetohydrodynamical components, i.e., the collapsing core, pseudodisk, accretion disk, wind, and funnel flow. In this report, we single out the effects of the X-rays on the accretion disk, which contributes to the buildup of the star and to the formation of planets.

2. The disk ionization rate

Our calculation of disk ionization builds on previous studies of the interaction of X-rays with interstellar gas, e.g., Krolik & Kallman (1983, henceforth KK). When a keV X-ray interacts with an atom or molecule, it produces a fast "primary" electron, which collisionally produces $(E - IP)/\Delta\epsilon$ "secondary" electrons, where IP stands for ionization potential and $\Delta\epsilon$ is the mean energy to make an ion pair ($\Delta\epsilon \approx 37\,\mathrm{eV}$ for H and He gas; Voit 1991). For atoms heavier than Li, inner-shell ionization is followed by the Auger effect, in which the excited, photoproduced ion undergoes two-electron decay rather than X-ray fluorescence, with the emission of several Auger electrons. The Auger electrons carry off a large fraction of the original excitation energy ($\sim IP$) and generate additional secondary electrons. As is well known (e.g., KK), most of the ionization is produced by the secondaries; each keV of secondary electron energy generates $1000/37 \approx 27$ ion pairs.

In addition to the microscopic physics of the X-ray interaction with matter, the following astrophysical factors enter into the calculation of the disk ionization rate:

X-ray Source - The more complete picture now available with *ROSAT* and *ASCA* suggests that YSOs generally have a quasi-steady hard component, and that they emit a roughly constant fraction ($\sim 10^{-4}$) of their total luminosity in X-rays (e.g., Feigelson et al. 1993, Casanova et al. 1995, Carkner et al. 1996). The observed range is $L_{\mathrm{XR}} = 10^{28.5} - 10^{31.5}\,\mathrm{erg\ s^{-1}}$. On top of the steady component, YSOs also can flare up to very high levels, sometimes $> 10^{32}\,\mathrm{erg\ s^{-1}}$ (e.g., Preibisch et al. 1993, 1995, Koyama et al. 1996). Much less is known about the geometry of the X-ray source, but a variety of observational and theoretical considerations on coronal activity, for both YSOs and closely related active stars (i.e., dMe and RS CVn systems), suggest source sizes of the order of $R_{\mathrm{X}} \sim 10\,R_{\odot}$, where R_{X} is the corotation radius (Shu et al. 1994).

X-ray Spectrum - We characterize the spectrum with a single temperature T_{XR}, and introduce a low-energy cutoff E_o to simulate the absorption of X-rays by the wind before they strike the disk.

Disk Model - In the absence of definitive information about the density and temperature variation of protostellar disks, we consider geometrically thin disks with a thermally-supported atmosphere such that radial distances $r >> H$, where H is the scale height. In the application considered below, we parameterize the disk with a mass surface density Σ and temperature T given as power laws in r: $\Sigma = \Sigma_o(r/R_o)^{-q}$, $T = T_o(r/R_o)^{-p}$. For numerical estimates, we use the minimum solar nebula of Hayashi et al. (1985): $R_o = 1\,\mathrm{AU}$; $q = 1.5$, $\Sigma_o = 1700\,\mathrm{g\ cm^{-2}}$; $p = 0.5$, $T_o = 280\,\mathrm{K}$. These relations imply that the scale height H and hydrogen number density n vary, respectively, as $H = H_o(r/R_o)^{1.25}$ and $n = n_o(r/R_o)^{-2.75}$, with $H_o = 6.72 \times 10^{11}\,\mathrm{cm}$ and $n_o = 1.17 \times 10^{15}\,\mathrm{cm^{-3}}$.

Cross-Sections - Because the X-ray absorption cross-sections increase strongly with atomic number, we introduce the usual total photoionization cross-section per H nucleus, $\sigma(E) = \sum_k x_k\,\sigma_k(E)$, where the sum is over the elemental abundances x_k and the cross-sections $\sigma_k(E)$ of each atomic species. We assume that X-ray photoionization is independent of molecular structure and that the disk is weakly ionized, and use the cross-sections compiled by Henke et al. (1993).

Dust Content - The total cross-section $\sigma(E)$ decreases rapidly with energy, (e.g., Morrison & McCammon 1983): $\sigma(E) = \tilde{\sigma}\,(E/\mathrm{keV})^{-n}$, with $n = 2.5 - 3.0$. Because the heavy elements contribute strongly to $\sigma(E)$, depletion is important. We consider sufficiently evolved protostellar disks, e.g., those around T Tauri stars, where the solids have both grown in size and settled to the disk midplane; in this case, $n = 2.810$, $\tilde{\sigma} = 8.50 \times 10^{-23}\ \mathrm{cm}^{-2}$.

Slant Factor and Vertical Column Density - The flux entering the disk is reduced by the usual inverse-square dilution and by a "slant factor" $R_X/r << 1$, which takes account the fact that the coronal X-rays approach the disk at a very small angle. This same factor also relates the vertical penetration depth to the distance the X-rays travel along the line of sight.

Figure 1 shows sample results for the model just described. The X-ray ionization rate ζ at $r = 1$ AU is plotted vs distance along the line of sight, measured by the absorption optical depth τ at 1 keV; the corresponding column density of H-nuclei is $N_{\mathrm{H}} \approx 5 \times 10^{21}\ \tau\ \mathrm{cm}^{-2}$. The X-ray source has $L_{\mathrm{XR}} = 10^{29}\ \mathrm{erg\,s}^{-1}$ and $R_{\mathrm{X}} = 12\,R_{\odot}$. The dash-dot curve shows the results for the case $kT_{\mathrm{XR}} = 1\,\mathrm{keV}$ and $E_o = 1\,\mathrm{keV}$. For all of the other curves, $kT_{\mathrm{XR}} = 5\,\mathrm{keV}$. The solid curve shows the results obtained with the higher temperature and the same low-energy cutoff, $E_o = 1\,\mathrm{keV}$. In both cases, the flattening of the ionization rate at small τ is due to the low-energy cutoff. Without this cutoff, which represents the absorption of soft X-rays by the wind, the rate would continue to rise below $\tau \simeq 1$, as shown by the dotted curve. This curve merges with the solid curve for $\tau \geq 2$, i.e., the cutoff is unimportant for the large optical depths of concern here.

Above $\tau = 1$, the rate falls off with ever increasing steepness; KK recommended a power law with index –1.6 for the case $kT_{\mathrm{XR}} = 1\,\mathrm{keV}$ and $1 < \tau < 100$. When $\sigma(E)$ is approximated by a power law, the ionization rate is well represented by a modified power law and is proportional to $\tau^{-a} e^{-B\tau^{b}}$. For example, in the case of severe heavy element depletion, the parameters are $a = 0.606$ and $b = 0.262$. The triangles in Fig. 1 show how well this approximation fits the full numerical calculations for $kT_{\mathrm{XR}} = 5\,\mathrm{keV}$ (solid curve).

The hardness of the X-ray spectrum is an important important factor at large disk column densities, as can be seen by comparing the solid curve ($kT_{\mathrm{XR}} = 5\,\mathrm{keV}$) in Figure 1 with the dash-dot curve ($kT_{\mathrm{XR}} = 1\,\mathrm{keV}$). At high τ (and, therefore, high X-ray energies), the bulk of the ionization comes from the most abundant heavy elements, whereas the small τ régime (low energies) is dominated by the light elements. The removal of the refractory elements from the upper disk atmosphere by grain settling allows the high energy X-rays to penetrate farther into the disk, reducing the ionization rate at low column densities ($\tau < 10$) and increasing it at high column densities ($\tau > 100$), as shown by the dashed line in Figure 1. At column densities > 1 g cm^{-2}, the surviving X-rays are in an energy range ($E > 10\,\mathrm{keV}$) where the absorption cross-section is smaller than the Compton cross-section. Consequently, Compton scattering will begin to alter the dependence of ζ on τ shown in Figure 1 when $\tau > 10^3$.

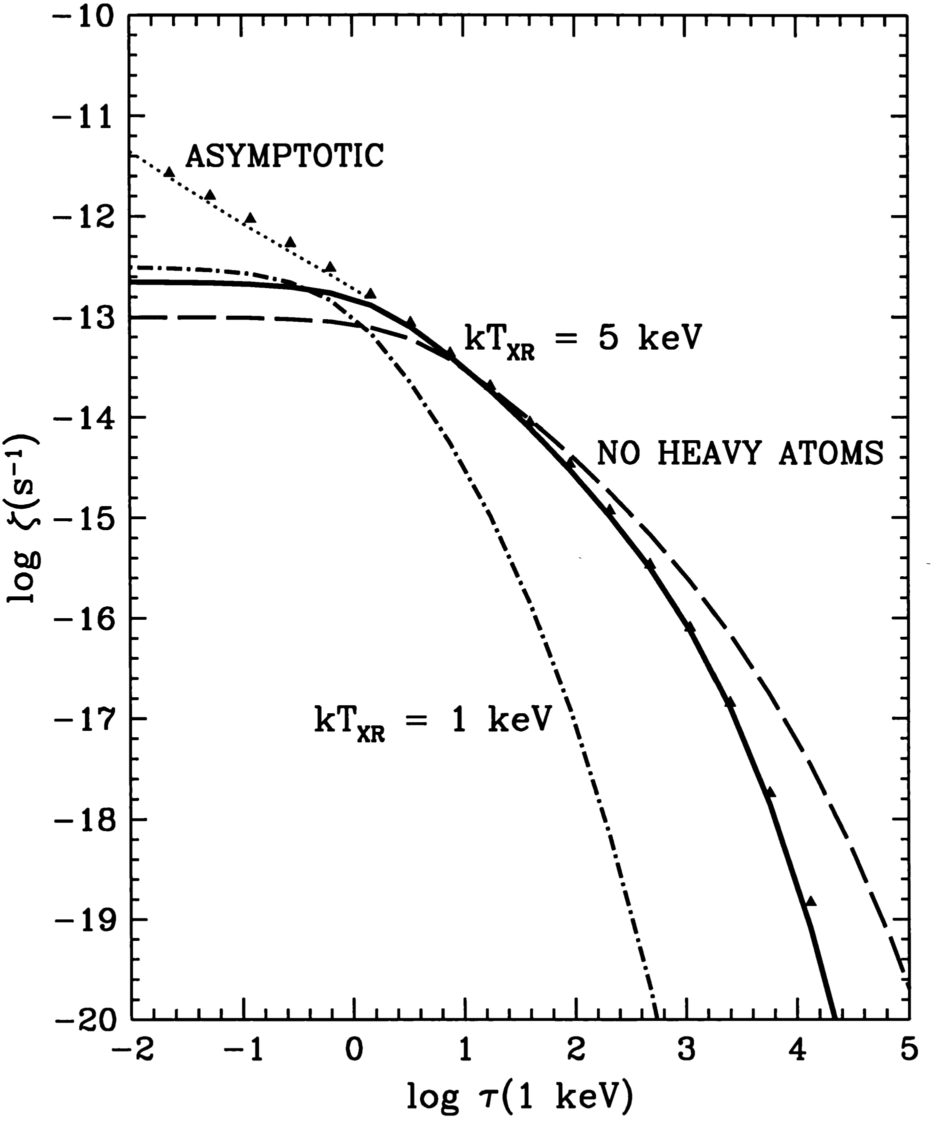

Figure 1. X-ray ionization rate in the disk at $r = 1\,\mathrm{AU}$ versus the optical depth at 1 keV. The X-ray source is located at the center of the disk $12\,R_\odot$ above the midplane; $L_{\mathrm{XR}} = 10^{29}\,\mathrm{erg\,s^{-1}}$. The dash-dot curve shows the results for $kT_{\mathrm{XR}} = 1\,\mathrm{keV}$; all other curves assume $kT_{\mathrm{XR}} = 5\,\mathrm{keV}$. In the exact calculation shown by the dotted line and in the asymptotic approximation indicated by the triangles, there is no low-energy cutoff; in all other cases, the cutoff is $E_o = 1\,\mathrm{keV}$. Cosmic abundances are assumed except in the case labeled "no heavy atoms" (dashed line), which illustrates severe heavy element depletion.

3. Discussion

We can summarize the results of the above calculation as follows. At a typical, intermediate location in the disk, the unattenuated ionization rate is very large, e.g., $\zeta \approx 10^{-13}\,\mathrm{s}^{-1}$ at $r = 1\,\mathrm{AU}$. Following along the line of sight, the rate decreases with distance (measured by the optical depth at 1 keV) according to $\zeta \sim \tau^{-a} e^{-B\tau^{b}}$, which is intermediate between a power law and an exponential. Figure 1 shows that ζ does not become as small as the Galactic cosmic ray ionization rate, $\zeta_{\mathrm{CR}} \approx 6 \times 10^{-18}\,\mathrm{s}^{-1}$ (Spitzer & Tomasko 1968), until $\tau \approx 65$ for $kT = 1\,\mathrm{keV}$ or $\tau \approx 2500$ for $kT = 5\,\mathrm{keV}$, demonstrating the superior penetrating power of hard X-rays. Recalling that $\tau(1\,\mathrm{keV}) = 1$ corresponds to visual extinction of $A_V =$ 2.5 magnitudes, we see that even soft X-rays ($kT = 1\,\mathrm{keV}$) provide high ionization rates along lines of sight with visual extinction up to $A_V \geq 100$ and up to $A_V \approx 1000$ for hard X-rays ($kT = 5\,\mathrm{keV}$). The limit for hard X-rays is determined by scattering rather than absorption, as noted at the end of Section 2. Because the X-rays enter the disk at a glancing angle (recall the slant factor mentioned above), scattering actually helps the X-rays penetrate downwards into the disk. The limit of vertical penetration is probably several Thomson mean-free-paths, or $A_V \approx 1000$ mag.

We have also made a preliminary calculation of the ionization fraction in a disk for the disk model described in Section 2, i.e., for a minimum solar nebula in which the (large) dust particles have sedimented to the mid-plane (for a more complete report, see Glassgold et al. 1996). In this case, recombination theory reduces approximately to $x_{\mathrm{e}} = (\zeta/n\beta)^{1/2}$, where β is an effective dissociative recombination coefficient and n is the local disk density. If small dust particles are present, their ability to scavage electrons from the gas has to be considered (e.g., Umebayashi & Nakano 1988). The model calculations show that stellar X-rays can ionize the outer layers of a nebular disk at intermediate radial distances, i.e., from a few tenths to several AU. The disk is warm enough at small distances for electronic collisions to ionize low-IP atoms. At large radii, the disk becomes thin enough for the X-rays to penetrate and ionize the entire the disk. However, for intermediate distances, the disk column density is so large that only the surface layers are ionized to any degree.

These qualitative statements are based on the criterion for coupling of the neutral disk matter to the magnetic instability discussed by Balbus & Hawley (1991), widely considered as a promising candidate for the origin of the viscosity of protostellar accretion disks. For this instability to be effective, the electron fraction in the disk has to be larger than some critical value, $x_{\mathrm{cr}} \approx 10^{-14} - 10^{-13}$ (Blaes & Balbus 1994, Gammie 1996). Thus, when we speak of large and small ionization fractions, it is with respect to this very small value of x_{cr}. Our conclusion is that X-rays are able to ionize the outer layers of protostellar accretion disks but not their interiors at intermediate radii. The result is a layered disk ionization structure, similar to that discussed by Gammie (1996) on the basis of external cosmic ray ionization. In this picture, the Galactic cosmic rays penetrate ~ 100 g cm^{-2} into the disk (Umebayashi & Nakano 1981) and produce an accreting surface layer that overlies a deeper, quiescent layer. For a disk viscosity parameter $\alpha \simeq 0.01$, Gammie finds that T Tauri disks can support disk accretion rates $\sim 10^{-7}\,M_{\odot}\,\mathrm{yr}^{-1}$. Because the coupled layer produced by X-rays is much smaller, comparable accretion rates require larger viscosity parameters, approaching $\alpha \sim 1$. The layered accretion produced by X-rays also differs from the case of cosmic rays in its sensitivity to the properties of the stellar X-ray source, especially the spectrum. Given the large range of observed protostellar X-ray properties, the disk ionization structure induced by X-ray irradiation leads to a range in disk accretion rates, unlike the case of Galactic cosmic rays.

It is also unlikely that Galactic cosmic rays actually reach the inner parts of accretion disks. It is more likely that they are excluded by the powerful winds generated by YSOs, in much the same way that the solar wind modulates the flux of Galactic cosmic rays. In the case of the Sun, the solar wind effectively excludes cosmic rays with energies < 100 MeV from the inner solar system, precisely the energies that are responsible for most of the interstellar cosmic ray ionization rate (Spitzer & Tomasko 1968). Thus, protostellar X-rays are probably an important if not the dominant source of nebular disk ionization.

The ionization of the accretion disk is just one example of the interaction of protostellar X-rays with the component flows involved in star formation. Because much of the X-ray spectrum is absorbed by the wind, we expect the soft X-rays to be important in ionizing the wind and in influencing the chemistry of the wind. The hard X-ray component will extend these effects to column densities up to 1000 magnitudes. In many cases, some of the X-rays escape the protstellar system and ionize the nascent cloud, as envisaged in earlier studies (e.g., Silk & Norman 1983, Krolik & Kallman 1983).

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Discussion

Irvine: For a solar-type star, how far out in the solar nebula would these effects compete with other energy sources, such as the interstellar UV field and galactic cosmic rays?
Glassgold: The hard X-rays can penetrate through ~ 1 gr cm^{-2} or more, equivalent to $\sim 1000\ A_V$, and thus be at least as effective as cosmic rays. Furthermore, the galactic cosmic rays are probably excluded by the stellar wind. The UV field generated by infall shocks may also be important.

Flower: Could you confirm that the fractional ionization of the gas, as computed, is extremely small?
Glassgold: Yes, the ionization levels are indeed small, e.g. the electron fraction for neutral-magnetic coupling is of order 10^{-13}.