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X-RAY EMISSION FROM PRE–MAIN-SEQUENCE STARS, MOLECULAR CLOUDS, AND STAR FORMATION

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ABSTRACT

The pre–main-sequence X-ray emitting stars observed in molecular clouds appear to provide the bulk of the ionization. Newly forming stars therefore control the coupling of the magnetic field to the cloud. Since this coupling itself is believed to be responsible for the rate of cloud collapse, we argue that there is a natural feedback mechanism, involving observed X-rays, which is capable of regulating molecular cloud evolution and the rate of star formation.

Subject headings: interstellar: matter — stars: formation — X-rays: general

The discovery of numerous X-ray sources identified with pre–main-sequence stars in molecular clouds may have profound consequences for molecular cloud evolution and star formation. Hitherto, almost 100 sources have been discovered with X-ray luminosities $\gtrsim 10^{30}$ ergs s^{-1} in several regions of active star formation. These include the Orion Nebula (Ku and Chanan 1979; Pravdo and Marshall 1981; Ku, Righini-Cohen, and Simon 1982); the Taurus-Auriga dark cloud complex (Gahm 1980; Feigelson and De Campli 1981; Walter and Kuhi 1981), and the Rho Ophiuchi dark cloud (Montmerle *et al.* 1983). Especially significant is the extreme youth of those sources identified with T Tauri or Hα emission-line stars; the winds from these sources may play an important role in molecular cloud support (cf. Norman and Silk 1980).

It has recently been noted that the incident X-ray flux in molecular clouds may be the dominant contributor to the cloud ionization, and the consequences have been examined for ion-molecule chemistry (Krolik and Kallman 1983). However, there is also a much more fundamental implication for the physics of star formation in X-ray–ionized molecular clouds. If X-rays from embedded protostars indeed provide a local control of the cloud ionization level, then the degree of coupling of the magnetic field to the cloud via ion drift (often called ambipolar diffusion, e.g., Nakano 1981) must depend on the star formation rate. However, ion drift itself regulates the rate of magnetic flux loss and thereby controls the rate of cloud collapse. Thus the rate of star formation both determines, and is determined by, the cloud ionization level. Our aim here is to further explore this feedback mechanism and derive the star formation rate in terms of directly observable protostellar X-ray characteristics.

The most detailed X-ray study of a molecular cloud thus far has been performed on the Rho Ophiuchi cloud (Montmerle *et al.* 1983). Within a projected area of approximately 10 pc^2, some 50 highly time-variable sources were found in the energy range from 2 to 10 keV. The inferred time-averaged intrinsic X-ray luminosity from the central region of the molecular cloud is approximately 5×10^{32} ergs s^{-1}. The spectra are consistent with optically thin thermal bremsstrahlung emission at a temperature $kT = 0.5$–2 keV. In arriving at this estimate, the observed X-ray flux over 2–10 keV has been corrected upwards by a factor of approximately 7 in order to allow roughly for absorption between us and a typical source, for X-rays outside the observed range, and for additional unresolved sources below the detection threshold of approximately 3×10^{29} erg s^{-1}.

The amount of molecular gas to which the observed X-rays are exposed is about $2 \times 10^3\ M_\odot$ in the central Rho Ophiuchi field. Ionizations by secondary electrons account for the bulk of the X-ray–induced ionization in the molecular cloud. To reasonable accuracy, we can ignore direct photoionizations and Auger ionizations and assume that 40 eV $\equiv E_i$ of photoelectron energy is expended, on the average, per H_2 ionization (Glassgold and Langer 1973). In addition, the presence of helium, with its large absorption cross section to photons below 1 keV, accounts for 2/3 of the photoelectrons. We can then infer the total volume-averaged hydrogen ionization rate: $\zeta = 1.5 \times 10^{-17}\ L_{33}\ M_3^{-1}\ s^{-1}$, where $L_{33} =$

$L_x/10^{33}$ ergs s^{-1} and M_3 is the molecular cloud mass in units of 1000 $M_\odot$.

Locally, the ionization rate can be considerably larger. Indeed, at distance R from a source,

$$\zeta = \int_{E_0}^{\infty} \left[(dL_x/dE)/4\pi R^2 \right] (E/E_i) \sigma(E) e^{-\tau(E)} \, dE/E, \tag{1}$$

where $\sigma(E)$ is the effective photoionization cross section for X-ray photons of energy E, E_0 is the photoionization threshold energy, and $\tau(E)$ is the optical depth to photons of energy E. For a thermal spectrum, characterized by temperature T_* and average luminosity L_x, we can approximate the integral for ζ by

$$\zeta = 1.3 \times 10^{-18} (L_x/10^{31} \text{ ergs s}^{-1}) \times R_{\text{pc}}^{-2} (1 \text{ keV}/T_x)^3 \tau^{-1-a} \text{ s}^{-1}, \tag{2}$$

where $R_{\text{pc}} \equiv R/1$ pc, the photon optical depth at energy $kT_\star$ $\tau = n\sigma_\star R$, the effective photoionization cross section per H atom at $kT_\star$ $\sigma_\star \approx 10^{-21}$ $(1 \text{ keV}/kT_\star)^3$ cm^2, n is the ambient H_2 density (assumed to be uniform), and $a \approx 0.6$ according to a numerical fit (Krolik and Kallman 1983).

The fractional ionization $n_e/n_{\text{H}} \equiv x$ in the cloud is determined by ion-molecular reaction rates, most of the electrons coming from helium ionization, and x depends only on the ratio ζ/n. The detailed dependence can be approximated by writing

$$x \approx 10^{-7} \left[(\zeta/10^{-17} \text{ s}^{-1})(10^4 \text{ cm}^{-3}/n) \right]^{\varepsilon}, \tag{3}$$

with $\varepsilon \approx 1/2$ at the densities of interest here (Oppenheimer and Dalgarno 1974; Elmegreen 1979). The earlier work found that $x \propto (\zeta/n)^{1/3}$. Observations of molecular ions in dense clouds directly yield $x \lesssim 7 \times 10^{-8}$ (Wooten, Loren, and Snell 1982). Evidently, the observed X-rays suffice to account for the observed ionization, and there is no need to postulate a flux of nonrelativistic cosmic rays interior to the cloud, as has been emphasized by Krolik and Kallman (1983). Note that interpretation of the *COS B* γ-ray source in terms of π^0 decays implies only a modest ($\sim$ 2) enhancement of the relativistic cosmic-ray flux relative to the main interstellar value.

Our principal interest here is in the implications of X-ray ionization for molecular cloud evolution. The magnetic field plays a crucial role in our discussion. If rotational forces are neglected for the moment, there is a critical cloud mass inferred from the virial theorem,

$$M_{\text{crit}} = (10/9\pi G)^{1/2} F/\pi, \tag{4}$$

above which collapse can occur. This is evaluated for a flattened spheroid: the numerical constant differs slightly for other geometries (Mestel and Paris 1979; Nakano 1981). Here $F = \pi B R^2$ is the magnetic flux, and we have neglected the surface pressure on the grounds that once collapse is initiated, the surface terms play a progressively more negligible role relative to the compressive gravitational force. In fact, there is a critical surface pressure above which the cloud cannot maintain an equilibrium state. At a higher pressure, free-fall collapse is inevitable, and pressure forces will not subsequently impede it.

Most molecular clouds are not undergoing gravitational collapse, however. The simplest hypothesis to account for cloud longevity is magnetic support, namely that cloud masses are below M_{crit}. For cloud masses below M_{crit}, ion drift results in magnetic flux loss by diffusion, reducing M_{crit} to the cloud mass M over a time scale t_D. We estimate t_D by assuming a quasi-static balance between gravity and magnetic pressure. For a polytropic cloud model in which density and ionization fraction have power-law radial dependences $\rho = \rho_0 (R/R_0)^\alpha$ and $x = x_0 (R/R_0)^\beta$, respectively, we find (with $\alpha \approx -2, \beta \approx 1$)

$$t_D = \left[\frac{4\pi\beta}{(\alpha+3)^3} \frac{G m_{\text{H}}}{x_0 \langle \sigma v \rangle} \right]^{-1} \approx 10^{14} x_0 \text{ yr}, \tag{5}$$

where σ is the ion-neutral collision cross section, v is the ion thermal velocity (e.g., Spitzer 1978), and x_0 and ρ_0 are the mean (external) ionization fraction and density.

Consider now the role of the embedded X-ray sources. Observations of stellar X-ray emission have shown that X-ray luminosity is inversely correlated with stellar age. The median X-ray luminosities of late-type stars can be fitted by (Feigelson 1982)

$$L_x = 6 \times 10^{31} (t/10^6 \text{ yr})^{-1} \text{ ergs s}^{-1} \equiv L_{x_0} (t/\tau)^{-1} \tag{6}$$

for $t > \tau \approx 10^6$–10^7 yr, a result understood empirically in terms of a correlation between L_x and rotational velocity (Pallavicini *et al.* 1981). This extrapolation tends to overestimate the X-ray luminosity of pre–main-sequence stars, for which a time-dependence weaker than t^{-1} is probably required.

If the rate of star formation is approximately constant, the cumulative effect of protostellar X-ray sources will result in a secularly increasing ionization rate in the cloud as a whole, although the flux from individual sources decays with time. For the moment, we suppose the mean background ionization level, x_0, to vary only slowly with time. Let us consider the ionization sphere around a newly formed protostellar X-ray source. We define this sphere to have such a radius that the ionization level in the interior exceeds the background level, namely

$$R = 0.5 (x_0/10^{-8})^{-5/18\varepsilon} (L_x/10^{31} \text{ ergs s}^{-1})^{5/18} \times (n/10^3 \text{ cm}^{-3})^{-0.72} (kT_\star/1 \text{ keV})^{1/2} \text{ pc}. \tag{7}$$

Within this region, the enhanced ionization effectively couples the magnetic field to the gas and inhibits further collapse. Only outside this region is the magnetic field diffusion time scale t_D (see eq. [5]) sufficiently short that collapse can proceed. Even there, $t_D \approx 10\ t_{\rm ff}$, more or less independently of density (assuming a constant ionization rate) (Nakano and Umebayashi 1980).

This suggests that the rate of formation of pre–main-sequence stellar X-ray sources may be self-regulating. The filling factor for the regions of enhanced ionization (and low star formation efficiency) must be of the order of unity. Too large a filling factor would allow enhanced star formation that would in turn ionize the cloud, increasing the filling factor, and inhibiting further star formation until the filling factor had dropped to be less than unity. In other words, the process of star formation is self-regulating, a negative feedback being provided via the ionization output of pre–main-sequence stars.

The maximum volume V_m of an ionization sphere around a protostar is determined by its scale before rotational decay of the protostellar dynamo reduces the X-ray flux over a time scale $\tau \sim 10^6$ yr. We assume that star formation occurs only in regions of unenhanced ionization, where secular magnetic flux loss occurs and lowers the local value of $M_{\rm crit}$ to stellar scales. The star formation rate is estimated as follows. Every time an ionization sphere V_m decays over time τ, a new protostar eventually forms. Thus the *mean* star formation rate within a molecular cloud is simply

$$S = \frac{1}{V_m \tau} = 4 \times 10^{-7} f \left(\frac{x_0}{10^{-8}} \right)^{5/6\varepsilon} \left(\frac{L_{x_0}}{10^{31}\ \text{ergs s}^{-1}} \right)^{-5/6} \times \left(\frac{10^6\ \text{yr}}{\tau} \right) \left(\frac{n}{10^3\ \text{cm}^{-3}} \right)^{2.2} \left(\frac{kT_\star}{1\ \text{keV}} \right)^{-3/2} \text{pc}^{-3}\ \text{yr}^{-1}. \quad (8)$$

The filling factor f is determined by the ratio of the time over which stars can actually form by magnetic flux diffusion and gravitational collapse relative to the decay time of a single ionization sphere. A simple argument yields $f = (1 + t_D/\tau)^{-1}$, where t_D is given by equation (5). This estimate accords well with the observed formation rate of low-mass stars. In one of the best studied regions, the Taurus-Auriga dark cloud complex, a study of NH_3 emission from dense condensations led Myers and Benson (1983) to predict that approximately 25 low-mass stars will form over approximately the next 2×10^5 yr. Similar rates were derived by Cohen and Kuhi (1979), who earlier used evolutionary tracks in the Hertzprung-Russell diagram to fix the ages of identified T Tauri stars. Since the volume of the complex is approximately 300 pc^3, these observationally inferred rates are in excellent agreement with the theoretical prediction of equation (8) if we assume $f \approx 1$, i.e., $t_D \lesssim \tau \approx 10^6$–$10^7$ yr, $x = 10^{-8}$–10^{-7}, the mean molecular density being about 10^3 cm^{-3}. Applying equation (8) to the Rho Ophiuchi cloud, we predict that, in the volume of approximately 10 pc^3 with $n \approx 3000$ cm^{-3} surveyed by Montmerle *et al.* (1983), nearly 100 pre–main-sequence stars have formed over the age of the cloud ($\approx 2 \times 10^6$ yr according to Cohen and Kuhi 1979. This is consistent with most of these stars having been detected as X-ray sources. It is especially interesting that our formation rate equation (8) depends only on *observed* parameters (in contrast, for example, to the model of Franco and Cox 1983).

Our model should be valid for $\zeta \lesssim 10^{-16}$ s^{-1}, when t_D is likely to be less than the time scale over which the protostellar X-ray sources are forming and decaying. Consider what happens when the mean ionization level increases as more and more X-ray–emitting pre–main-sequence stars form, owing to the relatively slow decay ($\propto t^{-1}$) of individual X-ray sources. Individual ionization spheres decrease in volume, but this actually enhances the efficiency of star formation since more regions of the cloud where the ionization rate is unenhanced can now collapse. At the same time, the increased background ionization level increases the diffusion time and tends to reduce the rate at which stars can form. These two opposing effects conspire to yield a weak increase in the net star formation rate. According to equation (8), $S \propto \zeta^{5/6-\varepsilon}$ if $f \ll 1$. Yet from equation (6) it follows that

$$\langle \zeta \rangle = \int L_x S\, dt \propto S(\ln t). \quad (9)$$

This leads to $S \propto (\ln t)^2$ if $\varepsilon = 1/2$. This logarithmic increase in S is obviously sensitive to the decay law adopted for L_x. Since L_x could decay less rapidly (cf. Walter 1981, who finds $L_x \propto t^{-1/2}$), a stronger secular effect is possible. In this case, our formulation cannot be extended to infer the evolution of S, since we implicitly assumed that S varied slowly. The characteristic time for this increase is the time for X-ray sources within the cloud to make a significant contribution to x_0. This is presumably approximately 10^6 yr. Because of the uncertainty in dependence of x_0 on ζ and the sensitivity of our result to this dependence, it is possible to conclude only that our X-ray model predicts a slow increase of the rate of star formation. There are indications in data on T Tauri star formation rates of such an effect (Cohen and Kuhi 1979).

The secular increase in mean ionization results in an increased efficiency of magnetic braking. Now magnetic braking occurs effectively only when the magnetic field diffusion time exceeds the Alfvén wave crossing time, $t_\parallel$ (Ebert, Von Hoerner, and Temesvary 1960), which is approximately equal to $t_{\rm ff}^0 (n/n_0)^{1+\varepsilon^{-1}}$, where $t_{\rm ff}^0$ is the initial free fall time and the cloud is initially magnetically supported. Power-law dependences of n and x on cloud radius are assumed as before. Since x_0 depends only weakly on n_0 and $\alpha \approx -2$, we see that, as the density increases, magnetic braking will eventually cease, and the cloud must stop losing angular momentum. All of this depends on the uncertain assumption that the field lines connect the cloud to the external medium; otherwise, the angular momentum loss may be greatly reduced. On the other hand, assuming connection, if the angle between rotation and field directions is large (as in Mouschovias and Paleologou 1979), the magnetic braking becomes more effective, with t_A being reduced by $\xi, 0.1 \lesssim \xi \lesssim 1$. Then the critical density above which angular momentum conservation may be expected to approximately hold is found to be

$$n_{\rm crit} \approx 20 n_0 \xi^{-1} (\zeta/10^{-17}\ {\rm s}^{-1})^{1/2}, \qquad (10)$$

where ζ now denotes the appropriate average over the cloud, and $\varepsilon \approx 1/2$.

At higher density, one can now sketch the evolution of the cloud as magnetic flux loss allows collapse to proceed. The specific angular momentum is

$$h = \Omega R_c^2,$$
$$= 1.7 \times 10^{21} \Omega_{15} M_1^{2/3} \Omega^{-2/3} n_3^{-2/3}\ {\rm cm^2\ s^{-1}} \propto \zeta^{-1/3}, \qquad (11)$$

where $\Omega_{15} = \Omega/10^{-15}$ rad s^{-1} is the corotation velocity at $n < n_3 = n_{\rm cr}/10^3$ cm^{-3}, and R_c denotes the radius of the region containing mass $M_1 = M/10\ M_\odot$ at density $n_{\rm crit}$. Mouschovias (1977) has noted that the residual angular momentum given by equation (11) may be identified with that in observed binaries, if it is assumed that the effective demise of magnetic braking can be parameterized by a range in $n_{\rm crit}$, 10^3 cm$^{-3} \lesssim n_{\rm crit} \lesssim 10^6$ cm^{-3}.

Mestel (1965) argued that the collapse proceeds until halted by centrifugal forces at a radius $R_f \approx h^2/GM$. Collapse can also occur along the rotation axis, until pressure forces result in the formation of a flattened disk with thickness $Z_f \approx R_f^2 v_s^2/GM$, where v_s is the sound velocity. Now the disk is unstable to fragmentation. The minimum fragment mass is of the order of $M_f \approx M\phi^4$, where

$$\phi = h v_s/GM = 0.32\, \Omega_{15} M_1^{-1/3} n_3^{-2/3} T_3^{1/2}, \qquad (12)$$

and the temperature within one of these dense protostellar blobs is $T_3 = T/1000$ K.

Now the mass M that we considered was an arbitrary volume of the cloud. Evidently, fragmentation results in the formation of blobs of centrifugally supported mass satisfying $\phi \lesssim 1$. According to equation (12), this yields the characteristic mass

$$M_{\rm min} \approx h v_s/G \approx 6 \Omega_{15}^3 \Omega_3^{-2} T_3^{2/3}\ M_\odot$$
$$\propto \zeta^{-1} n_0^{-2}. \qquad (13)$$

It is likely that the fragmentation will preferentially select low angular momentum matter, reducing the final angular momentum of an individual blob below $h \approx GM/v_s$. The bulk of the angular momentum must reside in orbital motions of binaries, or else be ejected by winds in the protostellar stage.

The inferred dependence of protostellar mass on ionization rate enables us to estimate the initial stellar mass function. For as ζ gradually increases with more and more X-ray–emitting pre–main-sequence stars forming, the minimum mass decreases. Consequently, a greater number of stars of lower mass continues to form before ζ increases any further. As ζ increases and $M_{\rm min}$ decreases, we infer from equation (13) that $dN/dM_\star \propto L_x^{-1} d\zeta/dM_\star \propto M_\star^{-2}$ [or $dN/dM_\star \propto M_\star^{-2.5}$ if $x \propto (\zeta/n)^{1/3}$], provided we assume that L_x is only weakly dependent on $M_\star$. Our inferred initial mass function is consistent with observations of dark clouds (Cohen and Kuhi 1979).

Formation of massive protostars can be enhanced by the increased ionization. For when $M < M_{\rm crit}$, as is the case for all clouds considered here, the angular momentum decreases with ζ according to equation (11). If $n_{\rm crit}$ (and ζ) are sufficiently large, then h will be decreased to the point where massive stars can form directly without any further fragmentation. This occurs if, at R_f, the density is high enough for the clump to be opaque and in effect become a protostar (Mestel and Paris 1979).

Finally, we remark that X-ray–regulated star formation is also likely to be important in active galaxies. In a Seyfert galaxy such as NGC 4151, a hydrogen ionization rate of the order of 10^{-17} s^{-1} is expected throughout the entire disk due to the observed central X-ray source alone. Our analysis suggests that vigorous star formation is likely to be correlated with X-ray activity, if sufficient gas is present.

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