Effects of the X-ray emission from young stars on the ionization level of a fractal star forming cloud

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Abstract. We present the initial results of a study aimed at computing the global effects of the X-ray ionization due to young stars within a molecular cloud that forms stars with a standard IMF at a rate accelerating with time. We model the gas distribution of the cloud as a fractal of dimension 2.3. We introduce the concept of a *Röntgen sphere* as the region around each PMS star where the ionization rate due to stellar X-rays exceeds that due to interstellar cosmic rays. Using values of the X-ray luminosity typical of T Tauri stars, we find that within the Röntgen radius the average ionization rate is increased by a factor 4 to 20 with respect to the value obtained from cosmic-rays.

1. Introduction

The initial results of the *Einstein Observatory* have shown that young stars are powerful X-ray emitters (Montmerle et al. 1983). It was then noted that the incident X-ray flux from YSOs may be the dominant controlling agent of the cloud ionization (Krolik & Kallman 1983). The possibility that X-ray ionization constitutes a natural feedback mechanism in the physics of star formation was suggested by Silk & Norman (1983). They argued that, in the framework of magnetically controlled cloud evolution and collapse, the rate of star formation both determines, and is determined by, the cloud ionization level. On a smaller scale, also the chemistry of the cloud around the immediate environs of a lowmass young star is deeply affected by the interaction of the high-energy photons with the dense molecular gas (Glassgold, Najita & Igea 1997).

The aim of this work is to re-examine the feedback mechanism of stellar X-rays on ambient gas in light of current views of the history of star formation in clusters and associations (e.g. Palla & Stahler 2000) and of the expanded knowledge of the X-ray properties of both embedded and optically revealed young stars (Feigelson & Montmerle 1999). Observational studies in a variety of star forming regions have indicated that the X-ray activity lasts longer and at higher levels than estimated in the initial studies. Also, it appears that molecular clouds do not spawn stars at constant rates during their lifetimes, but with a seemingly accelerating pattern. Finally, observations of molecular clouds have shown that with increasing spatial resolution the gas distribution breaks up into substructure of yet smaller scales. This suggests that the density distribution may have a fractal structure (e.g. Falgarone, Phillips & Walker 1991).

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Obviously, all these properties can enhance the impact of the interaction of the stellar X-rays with the surrounding medium. To assess such effects quantitatively, we have first examined the distribution of X-ray energy around a star with a characteristic X-ray luminosity $L_X/L_{\rm bol} \leq 10^{-3}$, typical of T-Tauri stars. We have then computed the overall contribution of the X-ray ionization due to an ensemble of stars formed inside a molecular cloud of sizes between 0.5 and 2 pc. The basic question we want to address is: what fraction of the mass of the cloud is affected by the enhancement in the ionization level due to X-rays?

2. The Röntgen Radius

The ionization rate, ζ_X , due to X-rays from a YSO as a function of distance, r, from the star can be evaluated from the expression:

$$\zeta_{\rm X} = 1.7 \frac{L_{\rm X} \tilde{\sigma}}{4\pi r^2 \Delta \epsilon} \frac{\int_{\nu_0}^{\infty} J_{\nu} \, e^{-\tau_{\rm X} \left(\frac{\nu}{\nu_{\rm X}}\right)^{-n} \left(\frac{\nu}{\nu_{\rm X}}\right)^{-n} d\nu}{\int_{\nu_0}^{\infty} J_{\nu} \, d\nu} \, {\rm s}^{-1} \tag{1}$$

where $L_{\rm X}$ is the X-ray luminosity of the star, $\sigma(E) = \tilde{\sigma}(E/1\text{keV})^{-n}$ is the total photoelectric cross section with n = 2.51 and $\tilde{\sigma} = 2.16 \times 10^{-22} \text{ cm}^2$. $\Delta \epsilon = 35$ eV is the mean energy to make a ion pair in weakly-ionized gas with cosmic abundance, and the factor 1.7 accounts for the ionization due to secondary electrons (Cravens & Dalgarno 1978). In eq. (1), $\tau_{\rm X} = n_{\rm H} \tilde{\sigma} r$ is the optical depth at $h\nu=1$ keV, J_{ν} is the monochromatic flux emitted from the star, in the standard assumption of a thermal bremsstrahlung spectrum. The minimum photon energy in the integral of eq. (1) is $h\nu_0 = 0.1$ keV. Assuming an X-ray luminosity of $L_{\rm X} = 10^{30}$ erg s⁻¹, the resulting run of the ionization rate with distance from the central star is displayed in Figure 1.



Figure 1. The X-ray ionization rate versus distance from the star, for a YSO with $L_{\rm X} = 10^{30}$ erg s⁻¹ and a two temperature spectrum model. $R_{\rm X}$ is the Röntgen radius.

As we see, interior to a radius $R_{\rm X}$ the ionization rate due to X-rays exceeds the background level provided by cosmic rays, here assumed at the constant value $\zeta_{\rm CR} = 10^{-17} \text{ s}^{-1}$. We call this X-ray dominated region the *Röntgen sphere*, and $R_{\rm X}$ the *Röntgen radius*. In the case of Fig. 1, the average ionization rate inside the sphere of constant density $n_{\rm H} = 10^4 \text{ cm}^{-3}$ is about 20 times that due to cosmic rays. We note that the uncertainty on the empirical value of ζ_{CR} is a factor of about five around our assumed value (e.g. van der Tak & van Dishoeck 2000).

To gauge the dependence of $R_{\rm X}$ and $\zeta_{\rm X}$ on the model parameters, we have considered X-ray emission spectra at different plasma temperatures, as well as the effects of an absorbing column density of $N_{\rm H} = 5 \times 10^{20} {\rm ~cm^{-2}}$ in front of the X-ray emitting region. As shown in Table 1, the Röntgen radius is insensitive to the input values, while the average ionization rate can vary by a factor of ~ 3 (the label *w* refers to the model with local absorption).

Table 1. Röntgen radius and average ionization rate

Plasma	kT	$R_{\mathbf{X}w}$	(Xw	$R_{\mathbf{x}}$	Сх
model	(keV)	(10^{17} cm)	$(10^{-17} \mathrm{s}^{-1})$	(10^{17} cm)	$(10^{17} \mathrm{s}^{-1})$
$2\mathrm{T}$	0.2 + 1	1.5	6.3	1.6	21.0
$1\mathrm{T}$	1	1.4	5.1	1.5	10.5
$1\mathrm{T}$	3	1.1	4.3	1.2	7.8

3. Star formation within a fractal cloud

The results of the previous section for an individual star can now be extended to an ensemble of young stars formed in a cluster/association. The assumptions that enter in the model are:

- The dense gas distribution has a fractal structure of dimension 2.3 (Falgarone, Phillips & Walker 1991). A fractal cloud model is obtained from hierarchically clustered points. Each point is divided into N=5 random points, all within a distance $1/L^h$ for hierarchical level h and geometric factor L = 2 (Elmegreen 1997). The fractal dimension is defined as $D = \log N / \log L \sim 2.3$. In Fig. 2 we display a rendition of the fractal gas distribution, integrated along the line of sight. Here, the gas density varies from 500 cm⁻³ to 10^6 cm⁻³ and the smallest structure is 2^{-6} times the characteristic size of the cloud (~1.5 pc).
- We assume that at t = 0 the cloud contains no stars. Star formation then begins and continues for 10 million years. Initially, the rate $\Psi(t)$ is low and then accelerates exponentially as $\Psi(t) \propto e^{\Delta t/t_c}$, with $t_c = 2$ Myr (Palla & Stahler 2000).
- At any time, star are formed randomly in mass in the interval 0.1–10 M_{\odot} . However, we require that after 10 million years their distribution

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Figure 2. Bidimensional representation of the fractal cloud with D=2.3.

 $\phi(m)$ follows a standard IMF $\phi(m) \sim m^{-\gamma}$, with γ given by, e.g., Scalo (1998). The behavior of both the star formation rate (SFR) and the mass distribution with time is displayed in the left panel of Figure 3.



Figure 3. Left panel: Time evolution of the SFR and mass distribution of 500 stars born in 10 Myr. Right panel: The evolution of the Röntgen radius in an ambient medium of 10^4 cm^{-3} during the PMS contraction of two stars of mass $0.1 M_{\odot}$ and $1 M_{\odot}$, respectively.

• We assume that the stellar X-ray luminosity is proportional to its bolometric luminosity: $L_{\rm X}(M_{\star},t) = 3 \times 10^{-4} {\rm L}_{\rm bol}({\rm M}_{\star},t)$. Each star has its associated Röntgen sphere, computed as in Sect. 2. Because of the variation of ${\rm L}_{\rm bol}({\rm M}_{\star},t)$ during PMS contraction, the Röntgen radius also varies with time, as illustrated in Fig. 3 (right panel).

4. X-ray ionization of a fractal cloud

Figure 4 shows a 3-D view of the evolution of a fractal cloud of size 1.5 pc following the prescriptions given above. Four different epochs are selected: regions coded in light gray represent the individual Röntgen spheres formed randomly within the cloud. After 10 million years, the cumulative X-ray luminosity of all the stars formed in the cloud is 6×10^{32} erg s⁻¹, and the overall star formation efficiency is about 16%.



Figure 4. Time evolution of the Röntgen spheres in the fractal cloud.

In a fractal cloud of size R_0 the mass enclosed in a radius R_X is proportional to $(R_X/R_0)^D$, where D is the fractal dimension. Thus, the mass fraction, F, of the cloud ionized by the stellar X-rays at time $t_f = 10^7$ yr can be computed as:

$$F(t_{\rm f}) = \int_{m_{\rm min}}^{m_{\rm max}} \int_0^{t_{\rm f}} \phi(m) \Psi(t) (R_{\rm X}(m, t_{\rm f} - t)/R_0)^D \ dm \ dt \tag{2}$$

where (m_{\min}, m_{\max}) is the range of stellar masses considered. Thus, we can estimate the total number of stars needed to have $F(t_{\rm f}) = 1$, i.e. complete overlap of the Röntgen spheres. In Table 2 we report these values for clouds with different sizes, along with the relative stellar density.

5. Conclusions

The preliminary results described above indicate that the X-rays produced by young stars in a cluster forming cloud may contribute significantly to its ionization degree, especially if the dense gas is not distributed uniformly. Typical

Cloud Size	N. stars	$ ho_{\star}$	N. stars _w	$ ho_{\star w}$
(pc)		(pc^{-3})		(pc^{-3})
0.5	90	700	100	800
1.0	400	400	500	500
1.5	800	250	1200	350
2.0	1500	190	2000	250

Table 2. Variation of the number of stars for F = 1

Röntgen radii vary between ~ 0.01-0.05 pc, with an enhancement of the ionization rate of a factor $\simeq 5-20$ over the value due to cosmic-rays alone. The mass fraction of a molecular cloud ionized by X-rays and cosmic rays is a function of the total number of stars and of their X-ray luminosity. For a fixed X-ray luminosity of $L_{\rm X} \sim 3 \times 10^{-4} L_{\star}$, the stellar density needed to fill a cloud of 1 pc size is about $\rho_{\star} \geq 500 \text{ pc}^{-3}$. The required number of stars, the total X-ray luminosity and the formation efficiency are thus comparable to those observed in cluster forming regions, such as ρ Ophiuchi. The ionization due to YSOs may therefore increase the coupling of the magnetic field to the cloud and the characteristic time of cloud core collapse via ambipolar diffusion. If star formation is indeed *accelerating*, the X-ray emission from YSOs can constitute a natural feedback mechanism to *decelerate* the process. More realistic models (including the effects of the dynamical evolution of the gas during star formation, a distribution of X-ray luminosity and emission spectrum as a function of mass and age, etc.) are being carried out to verify the initial results.

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