The effects of magnetic fields in cold clouds in cooling flows

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ABSTRACT

Large masses of absorbing material are inferred to exist in cooling flows in clusters of galaxies from the excess X-ray absorption in the spectra of some X-ray clusters. The absorbing material is probably in the form of cold clouds pressure–confined by the surrounding, hot, X-ray emitting gas. The cold clouds could remain relatively static until they are destroyed by evaporation or ablation, or give rise to star formation. If the final fate of the clouds is stars, the IMF of the stars formed over the whole cooling flow region \( r \sim 100 \, \text{kpc} \) should be biased to low masses, to avoid a very luminous, blue halo for the central galaxy of the cooling flow. However, there is evidence for bright star formation in the innermost \( r \lesssim 10 \, \text{kpc} \) regions of some cooling flows, and, therefore, the biasing of the IMF towards low masses should not occur or be less important at smaller radii. The consideration of magnetic fields may shed light on these two points. If magnetic fields are present, the magnetic critical mass should be considered, besides the Jeans mass, in establishing a natural mass scale for star formation. When this new mass scale is taken into account, we obtain the right variation of the biasing of the IMF with the radius in addition to inhibition of high-mass star formation at large radii. We also demonstrate that magnetic reconnection is a more efficient mechanism than ambipolar diffusion to remove magnetic fields in cold clouds.

Key words: magnetic fields – galaxies:clusters – cooling flows – intergalactic medium – stars: formation – X-rays: galaxies

1 INTRODUCTION

X-ray observations of cooling flows in clusters of galaxies have shown evidence of large masses of intrinsic X-ray absorbing material (White et al. 1991; Allen et al. 1993; Allen & Fabian 1997). The X-ray spectra show excess photoelectric absorption over that detected in our Galaxy, and require an absorbing column of \( \sim 10^{21} \, \text{cm}^{-2} \) covering the core of the cluster out to at least \( \sim 100 \, \text{kpc} \). The absorbing material is probably in the form of cold clouds embedded in the cooling flow (White et al. 1991; Ferland, Fabian & Johnstone 1994). The total amount of cold mass ranges from \( \sim 10^{11} \) to more than \( 10^{12} \, \text{M}_\odot \). These masses are in good agreement with those expected to accumulate from the cooling flows if the present deposition rates determined from deprojection of X-ray brightness profiles have been maintained during several Gyr. Only smaller masses of gas below X-ray-emitting temperatures have been derived from observations at wavelengths other than X-rays. Up to \( 10^8 \, \text{M}_\odot \) of ionized gas at \( \sim 10^4 \, \text{K} \) is present in some clusters within the inner few kpc, in the form of optical line-emitting filaments (Heckman et al. 1989), although masses \( < 10^6 \, \text{M}_\odot \) are more common. Molecular gas has been detected in the inner regions of Perseus via CO emission (Lazareff et al. 1989; Mirabel & Sanders 1989; Braine et al. 1995). Also in Perseus, neutral hydrogen has been discovered via absorption of diffuse radio emission by the 21 cm line (Jaffe 1990). All of these detections, other than X-ray absorption require cold gas to be present only at radii \( r \lesssim 15 \, \text{kpc} \). Moreover, apart from the Perseus cluster, only upper limits exist for the radio observations. Atomic hydrogen 21 cm observations limit the mass of optically thin HI to at most \( 10^9 - 10^{10} \, \text{M}_\odot \) (McNamara, Bregman & O’Connell 1990; Jaffe 1992; O’Dea, Gallimore & Baum 1995; Dwarkakath, van Gorkom & Owen 1994). CO observations yield limits of \( 10^8 - 10^{11} \, \text{M}_\odot \) for the mass in molecular hydrogen, applying the usual Galactic CO luminosity to \( \text{H}_2 \) mass conversion factors (O’Dea et al. 1994; McNamara & Jaffe 1994; Braine & Dupraz 1994; Antonucci & Barvains 1994). These upper limits are consistent with the \( 10^{5 - 6} \, \text{M}_\odot \) of molecular hydrogen at \( T \approx 1000 - 2000 \, \text{K} \) in the inner \( \sim 5 \, \text{kpc} \) of central cluster galaxies in cooling flows inferred from recent \( K \)-band spectroscopy of central galaxies in cooling flows, which has detected emission lines at \( 1.8 - 2.1 \, \mu \text{m} \) from \( \text{H}_2 \) \((1-0) \) through S(5) transitions (Jaffe & Bremer 1997; Falcke et al. 1998).

The final fate of the cooled gas has long been a puzzle, as mass deposition integrated over a Hubble time typically gives \( 10^{12} \, \text{M}_\odot \). The gas could accumulate as cold clouds
or collapse to form stars. It has previously been assumed that the cooled gas forms directly into low-mass stars with high efficiency (Fabian, Nulsen & Canizares 1982; Sarazin & O’Connell 1983; Schombert, Barsony & Hanlon 1993; Koupc & Gilmore 1994). The stars formed could not have a solar neighbourhood IMF, otherwise the galaxy at the centre of the cooling flow would have a very luminous, blue halo. If the gas ends up as starlike objects, the IMF should be biased to dim objects as red dwarfs, brown dwarfs or Jupiters. In fact, the conditions within cooling flows are so different from those in our own interstellar medium that the IMF of the stars formed is expected to be different from that in the Galaxy. Widespread cold clouds, however, are a possible sink for the cooled gas, so that star formation need not be very efficient (Daines et al. 1994), but the detection of the cold clouds has eluded both HI and CO observations (O’Dea et al. 1994, 1995).

Further problems, therefore, arise if the gas removed from the hot phase of the cooling flow is in the form of cold clouds. On the one hand, the clouds must cool very fast to a dense, very cold state, otherwise they would have a number of observational signatures: coronal lines, HI emission or absorption lines, and CO emission (Voit & Donahue 1995). On the other hand, they should be prevented from collapsing very fast into stars or low-mass objects, otherwise the cold phase would not have the large masses inferred from observations. In addition, there is evidence for massive star formation in the innermost regions of some cooling flows (Allen 1995, Smith et al. 1997), which allows one to infer that the suppression of star formation or the biasing of the IMF towards low masses does not occur or is less important at smaller radii. Therefore, at least in the inner regions of the cooling flow, cold clouds are been converted into stars.

In this paper we investigate the role of magnetic fields on the evolution of cold clouds in cooling flows, focusing especially on the effects of magnetic fields on star formation in the cold clouds. In previous papers (Jafelice & Friaça 1996, hereafter JF; Friaça et al. 1997), we explored the role of magnetic fields as heating source of the warm phase \((T \sim 10^4 \text{ K})\) of the cooling flow medium represented by the optical filaments. As a matter of fact, cooling flows clusters have important magnetic fields as revealed by high Faraday rotation measure (RM) observed in some of the most vigorous cooling flows (Ge & Owen 1993; Taylor, Barton & Ge 1994). Gordon et al. (1994) have found that all of the cooling flows with high RM at their centres have optical-line filaments or nuclear emission, which lead them to suggest that magnetic reconnection (MR) could power the emission lines of the optical filaments. However, our exploration of both MR (JF) and Alfvén waves (Friaça et al. 1997) as heating/ionizing source of the filaments, indicated that these mechanisms could not meet the energetic requirements of the most luminous filament systems. Nevertheless, magnetic fields can have a number of important consequences for the dynamics of the cooling flow as well for the evolution and formation of condensations arising out of the cooling flow (David & Bregman 1989; Loewenstein 1990; Loewenstein & Fabian 1990; Soker, Bregman & Sarazin 1991; Balbus 1991; Hattori, Yoshida & Habe 1995; Christodoulou & Sarazin 1996; Zobidi, Soker & Regev 1996, 1998). Magnetic fields are particularly important in supporting and confining the cold clouds (Daines et al. 1994). The shielding due to magnetic fields prevents the clouds from being evaporated by the surrounding \(1-7 \times 10^7 \text{ K}\) medium. On the other hand, magnetic fields should be removed of the cold clouds in order for magnetic support not to prevent the clouds from rapidly reaching the very low temperatures needed to elude detection via HI or CO lines.

Also with respect to the issues of inefficient luminous star formation as well as of the variation of the biasing of the IMF with radius, magnetic fields play an important role, since the natural mass scale for star formation, the Jeans mass, should be replaced by the magnetic critical mass if magnetic fields are present.

In Section 2, we compare the efficiency of ambipolar diffusion and MR as mechanisms for removing magnetic fields in cold clouds in cooling flows. Section 3 presents calculations of the evolution of cooling condensations in cooling flows with magnetic pressure and MR until the formation of cold clouds. Section 4 makes predictions on star formation along the cooling flow based on the magnetic critical mass as a mass scale for star formation. Our main conclusions are given in Section 5.

2 MAGNETIC SUPPORT IN COLD CLOUDS

Magnetic fields in cooling flows represent only a minor fraction of the ambient thermal pressure, \(\beta = P_B/P_{\text{gas}} = (B^2/8\pi)/nk_B T \approx 0.01\). (Note that, following the convention used in some studies on cooling flows [e.g., David & Bregman 1989; Donahue & Voit 1991], we define \(\beta = P_B/P_{\text{gas}}\), whereas in plasma physics, \(\beta_{pl} = P_{\text{gas}}/P_B\) denotes the “beta parameter” of the plasma.) Notwithstanding, they should be taken into account since magnetic pressure would dominate the dynamics of cold clouds that condense out of the cooling flow (David & Bregman 1989; Zobidi et al. 1998). As shown in simulations of the evolution of condensations in cooling flows (JF), in the beginning of the growing of the perturbation, the magnetic pressure is unimportant in comparison to the thermal pressure. However, as the gas within the perturbation cools, under conditions of frozen-in field, the component of the magnetic field perpendicular to the direction of compression increases \((B \propto \rho\) in plane-parallel geometry), and eventually \(\beta\) becomes > 1. At this stage, the cloud becomes magnetically supported and its compression is halted. After a phase of optical emission, corresponding to the optical filaments, the temperature drops so much that the optical emission is put out.

These extinguished filaments, whether they harbour star formation or not, are the end point for the mass removed in cooling flows and could be identified with the dark, cold clouds invoked by Daines et al. (1994) to explain the excess X-ray absorption in cooling flows. The final fate of the removed mass is naturally either faded filaments or a cooling flow population of mainly low-mass dim objects. If the strength of the remaining magnetic field in the filaments were high enough to support them against further collapse, the cloud could remain relatively warm due to heating by the surrounding X-ray emitting cooling flow. However, in this case the gas could be seen either in CO emission or in the 21 cm line. In addition, with no cold clouds, star formation would be suppressed, at least with observational evidence in favor of it. The maintenance of magnetic support also would avoid dust formation. Dust has been invoked
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(Hu 1992; Donahue & Voit 1993) to explain the line ratios of the optical filaments and colour maps reveal that dust features are common around central galaxies of cooling flows (Sparks, Ford & Kinney 1993; McNamara & O’Connell 1992, 1993, McNamara et al. 1996a, Pinkney et al. 1996). Dust widespread in the hot intracluster medium has also being suggested as responsible for the excess soft X-ray absorption in cooling flows instead of cold clouds, in view of the difficulties in eluding infrared, submillimiter, and radio detections of cold clouds (Voit & Donahue 1995). Very cold, dense, dusty clouds have been considered (Fabian, Johnstone & Daines 1994) as candidates for the absorbers giving the excess X-ray absorption in cooling flows. Some mechanism is needed to consume the magnetic field almost completely. In this way, magnetic support is removed, the cloud collapses and the temperature drops to very low values, thus allowing the formation of molecules and dust, as well as star formation.

Ambipolar diffusion has been invoked to remove magnetic fields in cold clouds in cooling flows (Daines et al. 1994). The timescale for this process is (McKee et al. 1993)

\[
 t_{AD} = \frac{3 < \sigma v >}{4\pi G \mu H m_{H}},
\]

or \( t_{AD} = 7.3 \times 10^{13} x_i \) yr, for the collision rate coefficient \( < \sigma v > = 1.5 \times 10^{-9} \) cm\(^3\) s\(^{-1}\) and \( \mu_H = 1.4 \) (\( \mu_H m_H \) is the mass per hydrogen nucleus), typical values for a cold molecular gas of solar abundances (Nakano 1984). The harder X-rays from the cluster maintain an ionization fraction \( x_i = n_e/n_H \geq 1.5 \times 10^{-5} \) in the cloud, even at very low temperatures (see next section). The implied timescale \( t_{AD} \geq 10^9 \) yr is very long.

As a matter of fact, a much more efficient mechanism for removing magnetic field is MR. The evolutionary models for optical filaments in cooling flows of JF have considered MR as the mechanism powering the line emission of the filaments. MR is expected to proceed at a rate

\[
 t_{MR} = \frac{l_{MR}}{M_{e\nu A}},
\]

where \( l_{MR} \) is the scale over which the MR takes place (i.e. the scale over which the magnetic field reverses its direction), \( V_A = B/(4\pi \rho)^{1/2} \) is the Alfvén velocity and \( M_e \) is the MR efficiency (\( M_e \) is the Alfvénic Mach number of the effective velocity \( V_e \) of the reconnection). For \( \beta < 1 \), MR occurs very slowly (\( M_e \ll 1 \)), however, for \( \beta > 1 \), there are several mechanisms of fast MR. Therefore, fast MR is expected to occur during the phase of optical emission of the condensations in cooling flows, when \( \beta \gg 1 \) due to the rapid cooling of the gas. For \( \beta > 1 \), \( M_e \approx 1/\ln R_m \) (Priest 1982), where \( R_m \) is the magnetic Reynolds number. From the definition of \( R_m \), \( R_m = V_{A\nu M/R} \eta \) (\( \eta \) is the magnetic diffusivity) and from \( M_e = 1/\ln R_m \), \( M_e \) is given by the solution of \( M_e \ln(M_e V_{A\nu M/R}) = 1 \), \( M_e \) is a very slowly varying function of \( V_{A\nu M/R} \eta \) for \( V_{A\nu M/R} \eta \) increasing from \( 10^{15} \) to \( 10^{25} \). \( M_e \) decreases from 0.032 to 0.019. In conditions typical of the intense optical emission phase (\( T \leq 10^5 \) K) of the condensations in cooling flows, \( M_e \approx 0.02 \) (JF). Considering \( \beta = 40 \), \( v_A = 80 \) km s\(^{-1}\), and \( l_{MR} = 10 \) pc as representative values of the optical emission phase (JF), the resulting time scale is \( t_{MR} \approx 6 \times 10^6 \) yr. This timescale is much shorter than \( t_{AD} \) (\( \geq 10^9 \) yr), and is comparable both to the duration of the purely X-ray emitting phase (\( \sim 3 \times 10^6 \) yr) and to that of the optical emitting phase (\( > 2 \times 10^6 \) yr) of JF models. Therefore, MR provides an efficient means of suppressing magnetic support in cold clouds in cooling flows.

3 EVOLUTION OF CONDENSATIONS IN THE COOLING FLOW AND FORMATION OF COLD CLOUDS

We have investigated the formation of cold clouds since the formation of condensations out of the hot phase (\( T \geq 10^7 \) K) of the cooling flow within the scenario outlined in Section 2. In order to study optical filaments in cooling flows, JF have performed calculations of cooling condensations in cooling flows from \( T = 10^7 \) K to \( T = 4 \times 10^5 \) K. Here, we extend JF calculations down to a temperature of 100 K, which would allow the formation of cold clouds in the central region of the condensation.

The evolution of the cooling condensations is obtained by solving the hydrodynamical equations of mass, momentum and energy conservation using a 1D hydrodynamical code (see Friaça 1993; Friaça & Terlevich 1998). Our simulations have been run with plane-parallel geometry using a Lagragian grid with 300 zones. The self-gravitation of the condensations is taken into account. Since there is no ion-
ionization equilibrium for temperatures lower than $10^6$ K, the ionization state of the gas at $T < 10^6$ K is obtained by solving the time-dependent ionization equations, for all ionic species of H, He, C, N, O, Ne, Mg, Si, S, Ar and Fe. We adopt a non-equilibrium cooling function for temperatures lower than $10^6$ K, since the recombination time of important ions is longer than the cooling time at these temperatures. The cooling function and the coefficients of collisional ionization, recombination and charge exchange of the ionization equations are all calculated with the atomic database of the photoionization code AANGABA (Gruenwald & Viegas 1992). The adopted abundances are solar (Grevesse & Anders 1989). Since the version of AANGABA used in JF did not include molecules, their cooling function was valid only for $T \gtrsim 5 \times 10^3$ K. In the present extension of JF calculations to lower temperatures, we use the equilibrium cooling functions and molecular fractions down to $T = 100$ K, given by a purely collisional model (Lepp et al. 1985, and references therein).

The clouds are modelled as slabs shrinking in the direction transverse to that of the cooling flow (which is the radial direction towards the cluster centre, since we assume spherical geometry for the cooling flow). The faces of the slab are in the plane of the magnetic field, so that the magnetic field is perpendicular to the direction of compression. The initial density perturbations are characterized by an amplitude $A$ and a length scale $L$, following $\delta \rho / \rho = A \sin(2\pi x / L)/(2\pi x / L)$, where $x$ is the direction of the compression (expansion) of the perturbation. We have also assumed that the perturbations are isobaric and non-linear ($A = 1$). The slab geometry is justified by the fact that the observed line emission is filamentary, which suggests that the perturbations are sheetlike rather than spherical. We start to follow the evolution of the perturbations from the nonlinear stage in view of the uncertainties about processes suppressing the growth of thermal instabilities in cooling flows.

In this work, we consider two models, representing perturbations evolving in the inner and in the outer parts of the cooling flow. In model A, representing the evolution of a cooling condensation in the inner cooling flow at a radius $r = 10$ kpc, the unperturbed $n_H = 0.1$ cm$^{-3}$ and $T = 10^7$ K are assumed. $L$ was fixed at 1 kpc for all the models. This length scale is suggested, for instance, by the spatial fluctuations in the velocity of optical filaments resolved in nearby cooling flows (Heckman et al. 1989). We fixed $\beta = P_B/P_{gas} = 0.1$ for the unperturbed medium, a representative value for the range of $\beta = 0.01 - 1$, expected in the central 10 kpc of cooling flows. We have considered that MR proceeds at an efficiency $M_t = 0.02$. The MR heating is turned on only for $\beta > \beta_{on} = 1$. The value of $l_{MR}$ used in eq. (2) is derived assuming that the magnetic field suffered a 1D compression as the gas condensed from the intracluster medium to form the condensations. The smoothness of the radio images of radio haloes in clusters imply a correlation length of the magnetic field $l_c \lesssim 15$ kpc (Tribble 1993). During a 1D compression, the quantity $l_{nH}$ is conserved. Assuming $l_{t,ICM} = 10$ kpc and $n_{H,ICM} = 10^{-3}$ cm$^{-3}$ for the intracluster medium, $l_{nH} \equiv l_n$ within the condensations is obtained from the local $n_H$.

Model B, describing the outer cooling flow ($r = 100$ kpc) has $M_t = 0.02$ and $\beta_{on} = 1$, and unperturbed $L = 10$ kpc, $n_H = 5 \times 10^{-3}$ cm$^{-3}$, and $T = 7 \times 10^7$ K. The radial variation of $n_H$ and $T$ assumed in models A and B follows X-ray spectroscopic studies and image deprojection analysis which allow to derive temperature gradients and the density runs with radius. The radial dependence of the density implied by models A and B, $n_H = 5 \times 10^{-3}(r/100$ kpc)$^{-1.30}$ cm$^{-3}$, is consistent the averaged radial profile of $n_H = (4.64 \pm 0.88) \times 10^{-3} (r/100$ kpc)$^{-1.26 \pm 0.19}$ cm$^{-3}$ found by White, Jones & Forman (1997) in their sample of large ($M > 50 \ M_\odot$ yr$^{-1}$) cooling flows detected with the Einstein Observatory. With respect to the temperature gradient, the cooling flow region $10 \lesssim r \lesssim 100$ kpc separates the inner cooling flow, where the gas temperature approaches the virial temperature of the central galaxy (typical $\sigma = 300$ km s$^{-1}$ or $T = 6.6 \times 10^8$ K) from the general ICM, with a temperature roughly equal to the cluster virial temperature (typical $\sigma = 1000$ km s$^{-1}$ or $T = 7.5 \times 10^7$ K).

For model B, the unperturbed value of $\beta$ was derived from the relation of the magnetic field at the inner radius $r_i = 10$ kpc (model A) to the magnetic field at the outer radius $r_o = 100$ kpc (model B) following Soker & Sarazin (1990). We assume: 1) frozen-in field; 2) spherical symmetry for the flow; and 3) that at the outer radius $r_o$ the field is isotropic, i.e. $B_{i,o}^2 = B_{e,o}^2/2 = B_o^2/3$ and $l_{e,r} = l_{o,t} \equiv l_o$ (where $B_{e,r}$ and $B_{o,t}$ are the radial and transverse components of the magnetic field $B_o$ and $l_{o,t}$ and $l_o$ are the coherence length of the large-scale field in the radial and transverse directions). In the discussion of Soker & Sarazin (1990), the inward cooling flow is assumed to be homogeneous. However, detailed studies of the observed X-ray brightness profile of cooling flows have revealed that $M$ is not constant with radius, but that it decreases towards the centre following approximately $M \propto r$ (Thomas, Fabian & Nulsen 1987). Therefore, we modified the calculation of the magnetic field of Soker & Sarazin (1990) by considering an inhomogeneous cooling flow (i.e. $M_l \neq M_o$). Since we are modelling the condensations responsible for removing the mass in the flow as slabs containing the magnetic field, and since the magnetic field lines become increasingly radial as the gas flows inward, we assume that the condensations are parallel to the radial direction. For a homogeneous inflow and frozen-in field, $l_{i,t} = l_{e,o}(u_i/u_o)$ ($u$ is the inflow velocity), and $l_{t,i} = l_{t,o}(r_i/r_o)$, but in inhomogeneous flow, in which magnetic field is being removed from the flow by condensations compressed in the transverse direction, the $l_{i,t} - l_{t,o}$ relation has to be modified to $l_{i,t} = l_{t,o}(r_i/r_o)(M_i/M_o)^{-1/2}$. The two components of the field are then given by

$$B_{i,t}^2 = \frac{1}{3} B_o^2 \left( \frac{r_i}{r_o} \right)^{-4} \left( \frac{M_i}{M_o} \right)^2$$

and

$$B_{i,t}^2 = \frac{2}{3} B_o^2 \left( \frac{r_i}{r_o} \right)^{-2} \left( \frac{M_i}{M_o} \right) \left( \frac{u_i}{u_o} \right)^{-2}.$$  

Assuming that $M \propto r$ (and from $M = 4\pi r^2 \rho m_H u_H u$), the field strength $B_o$ is given by

$$B_o^2 = 3B_i^2 \left[ \left( \frac{r_i}{r_o} \right)^{-2} + 2 \left( \frac{r_i}{r_o} \right) \left( \frac{n_{H,i}}{n_{H,o}} \right)^2 \right]^{-1}.$$  

The unperturbed values of $n_H, T$, and $\beta$ of model A ($n_{H,i} = \ldots$)
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0.1 cm\(^{-3}\), \(T_i = 10^5\) K, and \(\beta_i = 0.1\) imply \(B_i = 28.2\) \(\mu\)G, and, from eq. (5) and unperturbed \(n_H\) and \(T\) of model B (\(n_{H,o} = 5 \times 10^{-3}\) cm\(^{-3}\) and \(T_o = 7 \times 10^5\) K), we obtain \(B_o = 3.64\) \(\mu\)G and \(\beta = 4.76 \times 10^{-3}\) for model B.

The hydrogen column density of hydrogen nuclei \(N_H\) is \(4.90 \times 10^{20}\) cm\(^{-2}\) for model A and \(2.45 \times 10^{20}\) cm\(^{-2}\) for model B. Note that for a planar cloud, under hydrostatic equilibrium, the pressure \(P_c\) in the midplane is given by \(P_c = P_o = (\pi/2)Gn_S^2\), where \(n_S\) is the surface mass density, and \(P_0\) is the external pressure, or \((P_c - P_0)/kB = 4.3 \times 10^3N_{21}\) cm\(^{-3}\) K, where \(N_{21} = 10^{22}\) cm\(^{-2}\), implying \((P_c - P_0)/kB = 2.1 \times 10^{-5}(1.1 \times 10^4)\) cm\(^{-3}\) K for model A(B). Since \(P_0/kB = 2.3 \times 10^7(8 \times 10^7)\) cm\(^{-3}\) K for model A(B), the cooling condensations are confined by the pressure in the surrounding cooling flow, not by their self-gravity.

Other implication of our column densities is that the surrounding X-ray flux from the cooling flow maintains a significant degree of ionization at the centre of the cloud, even when very low temperatures are attained. The model of Ferland et al. (1994), describing a slab embedded in the radiation field typical of a cooling flow with inflow rate of 100 M\(_\odot\) yr\(^{-1}\) at the cooling radius of 100 kpc, predicts an ionization fraction \(x_e \simeq 1.5 \times 10^{-5}\) at a depth of \(N_H = 1 - 2.5 \times 10^{20}\) cm\(^{-2}\). Since in both our models A and B, the surrounding cooling flow environment is more vigorous (\(nT = 2.3 \times 10^7\) and \(nT = 8 \times 10^5\), respectively) than in Ferland et al. model (\(nT \approx 3 \times 10^5\)), the highest X-ray flux would lead to even higher ionization levels.

Figure 1 shows the evolution of temperature, density, the ratio \(\beta\), and magnetic field strength in the innermost cell, for models A and B, since the beginning of the optical emitting phase (defined when the temperature in the innermost cell drops below 5 \(\times\) 10\(^5\) K). The duration of the first, purely X-ray emitting phase (when \(T > 5 \times 10^5\) K throughout the condensation) shows little dependence on the efficiency of MR: it varies from 3.2 \(\times\) 10\(^6\) (1.57 \(\times\) 10\(^7\)) yr to 3.3 \(\times\) 10\(^6\) (1.58 \(\times\) 10\(^8\)) for model A (B) as \(M_o\) varies from 0 to 0.02. Here we focus our discussion on the late (beyond the purely X-ray emitting phase) evolution of the condensation, and, in general, the times will be counted from the beginning of the optical phase. The duration of the optical phase (during which the filament most strongly emits optical lines) can be estimated from the time for the gas in the centre of the condensation (the values of all quantities discussed in this section are given in the central region of the condensation) to cool from \(T = 5 \times 10^5\) K to \(T < 5 \times 10^3\) K: 1.4 \(\times\) 10\(^7\) yr and 2.4 \(\times\) 10\(^7\) yr for models A and B, respectively. Note that, although the duration of optical emitting phase is similar for both models, the purely X-ray emitting phase lasts much longer for model B than for model A, for which the two timescales are comparable. Due to this fact, the condensations in the inner cooling flow are much more efficient emitters of optical lines than the condensations in the outer cooling flow, which spend a negligible span of their lifetime in the optical phase.

For model A, the centre of the condensation takes 1.66 \(\times\) 10\(^7\) yr to cool from 5 \(\times\) 10\(^5\) K to 100 K. One can distinguish three stages in the late evolution of the condensation: a hot stage (with \(2 \times 10^4 < T < 5 \times 10^5\) K); a warm stage (4000 < \(T < 2 \times 10^4\) K); and a cold stage (100 < \(T < 4000\) K). These stages correspond to the presence or not of thermal instability: the hot stage is thermally unstable, the warm stage corresponds to the thermally stable regime around \(T \sim 10^4\) K, and the cold stage include the unstable region between \(\sim 2000\) and \(\sim 4000\) K, in which the cooling function falls rapidly with temperature. As a consequence, the filament shows a very short (10\(^5\) yr) hot stage, a long (1.41 \(\times\) 10\(^7\) yr) warm stage, and a relatively short (2.5 \(\times\) 10\(^6\) yr) cold stage. The most slowly varying quantity is the magnetic field, which first rises from an initial value 105 \(\mu\)G to 136 \(\mu\)G at \(t = 8.5 \times 10^5\) yr, and then decreases to a final value 88.8 \(\mu\)G. The evolution of the magnetic field shows fluctuations of a factor \(\sim 1.5\) around the average \(B\). The fluctuation of a factor \(2 - 2.5\) at \(t = 1.4 \times 10^7\) yr is due to the gas having reached the thermally unstable part (2000 \(\lesssim\) \(T\) \(\lesssim\) 4000 K) of the cooling function. \(\beta\) shows a peak value of 180 at \(t = 2 \times 10^5\) yr, and then decreases to a local minimum of 13.3 at \(t = 1.4 \times 10^7\) yr. Shortly after this time, the gas reaches the 2000 \(\lesssim\) \(T\) \(\lesssim\) 4000 K unstable domain, and \(\beta\) suddenly rises to \(\sim 55\) due to the rapid drop of the temperature and the increase of density to keep pressure equilibrium. At the end of the cold stage, \(\beta\) returns to the \(\sim 10\) level. It is important to note that in model A, MR was unable to consume the magnetic field, (i.e. to reduce \(\beta\) to \(\lesssim 1\)), at least down to a temperature of 100 K. The nearly constancy of the magnetic field (only a 15 % decrease from \(5 \times 10^5\) K to 100 K) suggests that the value of \(B\) at even lower temperatures is not significantly lower than the value at \(T = 100\) K, and, therefore, that magnetic pressure keeps dominating over thermal pressure.

For model B, the core of the condensation cools from \(5 \times 10^5\) K to 100 K in 2.46 \(\times\) 10\(^7\) yr. The duration of the hot, warm, and cold stages are 3 \(\times\) 10\(^5\) yr, 2.4 \(\times\) 10\(^7\) yr and 6 \(\times\) 10\(^7\) yr, respectively. The MR heating is more effective in model B, and the stable, warm stage begins closer to \(T = 3 \times 10^4\) than to \(T = 2 \times 10^5\) as in model A (in model B, T decreases from \(3 \times 10^4\) K to \(2 \times 10^4\) K in \(4 \times 10^6\) yr). The values of \(B\) and \(\beta\) are lower than in model A. Again, the more slowly varying quantity is \(B\), which a decrease of 35% from \(B = 58.9\) at \(t = 0\) to 39.9 \(\mu\)G at the end of the calculations. A maximum \(B = 64\) \(\mu\)G is reached at \(t = 6.4 \times 10^6\) yr. \(\beta\) has a maximum of 115 at \(t = 10^6\) yr, and then decreases until it becomes \(\approx 1\) at \(t \simeq 2.4 \times 10^7\) yr. At this point, the temperature plummets from \(T \approx 7000\) K to \(T \simeq 300\) K because the magnetic pressure support has been removed, and the density has increased drastically to maintain the pressure equilibrium, thus reducing the cooling time. Moreover, the gas has reached the thermally unstable region of the maximum of the cooling function between \(\sim 2000\) K and \(\sim 4000\) K. The spike in \(\beta\) and the smaller one in the magnetic field are the result of the sudden compression of the gas, leading to a temporary overpressure in the magnetic field, which is soon consumed by MR. The high density reached by the gas explains the short duration of the cold stage. In contrast with model A, in model B the magnetic support is removed by MR when \(T \sim 7000\) K, and, after the temporary increase in \(\beta\) in the unstable region \(2000 \lesssim T \lesssim 4000\) K, a situation with \(\beta \approx 1\) is established.

A comparison between the time scales for cooling (\(t_c\)) and for MR (\(t_{MR}\)) allows one to understand the reason of MR having consumed magnetic energy in model B down to \(\beta \sim 1\) while \(\beta\) remains \(\sim 10\) in model A. The two time scales set the pace for the decrease of temperature and \(\beta\), respectively. As shown in Section 4, the ratio \(t_{MR}/t_c\) is smaller.

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in model B than in model A since the onset of MR, during the purely X-ray emitting phase of the evolution of the perturbation. As a consequence, during this early evolutionary phase, the magnetic pressure was already more rapidly consumed in model B than in model A (the initial values of $\beta$ in the optical phase are 151 and 100 for model A than for model B, respectively). During the optical phase, the trend of more efficient magnetic field consumption in model B than in model A persists, as one can see from the smaller values of $t_{\text{MR}}/t_{\text{c}}$ for model B: at the beginning of the warm stage (then $T = 2.9 \times 10^4$ K for model A, and $T = 1.9 \times 10^4$ K for model B), $t_{\text{MR}}/t_{\text{c}} = 99(60)$ for model A (B), and when the temperature drops to $T = 10^4$ K (at $t = 8 \times 10^6$ yr and $1.4 \times 10^7$ yr, for models A and B, respectively), $t_{\text{MR}}/t_{\text{c}} = 55(34)$ for model A (B). In addition, during the optical phase, model A becomes closer to the ionization equilibrium than model B, as we can see from the comparison of the $n_{\text{HI}}/n_{\text{H}}$ ratio at $T = 10^4$ K of model A (96.8%) and model B (44.5%) to the equilibrium value (99.7%). As a consequence, the cooling function of model A approaches the equilibrium cooling function, which is higher than the extreme non-equilibrium cooling function (i.e. that obtained in conditions of pure cooling without heating), thus reducing the cooling time. This shows the importance of a proper calculation of the cooling function from the actual ionization state of the gas: the non-equilibrium plasma is over-ionized for its kinetic temperature because the recombination time of important ions was comparable to the evolutionary time of the perturbation, and in this case, the actual cooling rate is lower than the equilibrium value because the highly excited species cannot be efficiently excited by impact.

It should be noted that for the high values of $\beta$ typical of the inner cooling flow, MHD instabilities can occur, which can have interesting effects on the evolution of the perturbation that have not been considered in this paper. In particular, if the cloud is part of another structure, depending on the curvature radius of the structure in which the perturbation is embedded, magnetic tension can play an important role. Then, in the evolution and motion of the perturbation, besides other factors — radiative cooling, thermal and magnetic pressure, buoyancy, drag — magnetic tension should also be considered (Zoabi et al. 1996). For instance, if the perturbation is located in the lower part of a U-shaped magnetic flux tube (formed from the reconnection of two neighbouring radially elongated flux loops), the magnetic tension force could uplift the filament from the inner region of the cooling flow to a few 10 kpc from the cluster center (Zoabi et al. 1996). Another possible situation is that of a perturbation located in the lower part of a loop of magnetic flux inflowing with the cooling flow (Zoabi et al. 1998). Then, the denser, lower part of the loop cools till catastrophic cooling, when MR occurs, freeing the lower segment, which falls inward and may become an optical filament, and eventually ends up as cold clouds.

4 STAR FORMATION IN MAGNETIZED COLD CLOUDS

There is substantial evidence in favor of star formation in cooling flows. The blue light excess over that expected from the underlying galaxy that has been observed in many massive cooling flows (Johnstone et al. 1987; Romanishin 1987; McNamara & O’Connell 1989; Allen et al. 1992; Crawford & Fabian 1993; Crawford et al. 1995) has been interpreted as due to young, massive stars (Johnstone et al. 1987; McNamara & O’Connell 1989). Although an alternative explanation of the blue light excess in terms of scattered nucleus emission (McNamara & O’Connell 1993; Crawford & Fabian 1993) is also consistent with the data, at least in the case of a few clusters, e.g. Perseus (Rubin et al. 1977; Shields & Filippenko 1990), Abell 2199 (Bertola et al. 1986), and Hydra A (Hansen, Jorgensen & Norgaard-Nielsen 1995, Melnick, Gopal-Krishna, Terlevich 1997), this emission is clearly stellar since strong Balmer absorption lines can be seen. Star formation is also suggested by Mg$_2$ index and by 4000-Å break measurements, which indicate recent star formation in central galaxies of cooling flows with optical filaments (Cardiel, Gorgas & Aragón-Salamanca 1995, 1998).

In addition, simple modelling of the optical spectra of the central galaxies of clusters with cooling flows, indicate the presence of $\gtrsim 10^6$ O stars in the central $\sim 10 - 20$ kpc of the most massive systems (Allen 1995). In some massive cooling flows, the central galaxy contain large numbers of Wolf-Rayet stars, which provides evidence for the formation of very massive stars ($M \gtrsim 30$ M$_{\odot}$). The U-B color excess in the centre of the cooling flow allow to infer star formation rates ranging from a few to a few tens of M$_{\odot}$ yr$^{-1}$ in the central $\sim 10$ kpc of the cooling flow (McNamara & O’Connell 1989, 1993). Although some massive star formation is occurring in the inner regions of the cooling flow, there are a number of stringent observational limits on massive star formation throughout the cooling flow (see Fabian 1994), so that a star formation with a standard IMF (Scalo 1986) is excluded. The star formation should be very inefficient or skewed toward low mass stars (or even brown dwarfs and Jupiters) in the $r \gtrsim 10$ kpc region, otherwise the central galaxy would be too luminous and blue.

The physical conditions in cooling flows are very different from those in the Galaxy and, as a consequence, it is expected that the IMF will differ from that of the solar neighbourhood. In particular, the pressure in the cooling flow is $\sim 100$ times larger than that of our interstellar medium. As a result, the Jeans mass (McKee et al. 1993)

$$M_J = 11.5 \frac{(T/10^4 \text{K})^2}{(\rho v/10^3 \text{cm}^{-3} \text{K})^{1/2}} \text{M}_{\odot}$$

is reduced by a factor of $\sim 10$ with respect to the typical value for the solar neighbourhood. In this way, the IMF is skewed towards small masses (Fabian, Nulsen & Canizares 1982; Sarazin & O’Connell 1983). This then explains why so little star formation is ever seen around central cluster galaxies: the stars that are formed are too faint to be easily detected.

The above reasoning, however, does not take into account magnetic fields, which, as shown in Section 2, dominate the dynamics of the cold clouds. The primary effect of magnetic fields in cold clouds is to stabilize them against gravitational collapse (Loewenstein & Fabian 1990). In addition, the comparison of the observed IMF with calculations of the IMF including several instability criteria, shows that magnetic fields are needed to reproduce both the position of the peak and the shape of the IMF (Ferrini, Palla & Penco 1990). In the presence of magnetic fields, the Jeans
A solution to this dilemma is given by the fact that, in the presence of magnetic fields, \( M_B \), the critical mass for the collapse of a magnetized cloud, is the parameter regulating the star formation at least in the high mass end of the IMF. In the case of cooling flows, \( M_B \) in the inner regions, \( M_B = 1243 \, M_{\odot} \), is comparable to the Galactic value of \( \sim 500 \, M_{\odot} \) and, therefore, the star formation is expected to be not so different from that in the Galaxy, that is, the IMF will include massive stars. On the other hand, in the outer regions of the cooling flow \( M_B = 16.3 \, M_{\odot} \), which is much smaller than the value in the Galaxy and, therefore, the star formation must have characteristics very different from the Galactic one, implying an inhibition of massive star formation or a displacement of the masses of the objects formed to lower values, typical of red dwarfs, brown dwarfs or Jupiters. The considerations above can be the missing link in the scenario in which there are differences of star formation efficiency between the outer and the inner cooling flow.

Table 1 also shows the ratio between \( t_{MR} \) and the cooling time \( t_c = (5/2)kT/nT \) when the initial perturbation has cooled from the environment cooling flow temperature enough to reach \( \beta = 1 \) (then, model A shows \( n_H = 0.23 \, \text{cm}^{-3} \), \( T = 2.34 \times 10^6 \, \text{K} \), and \( B = 66 \, \mu \text{G} \), and model B \( n_H = 5.1 \times 10^{-2} \, \text{cm}^{-3} \), \( T = 3.42 \times 10^6 \, \text{K} \), and \( B = 37 \, \mu \text{G} \)). At this point, MR is turned on for the first time. As we see from Table 1, the MR is more efficient in model B than in model A. For this reason, in model B, MR has consumed very efficiently the magnetic field, and \( \beta \approx 1 \) is reached before the temperature has dropped to 100 K.

### 5 CONCLUSIONS

We have calculated typical timescales of MR and ambipolar diffusion in conditions prevailing in cold clouds formed in cooling flows and conclude that MR is far more important than ambipolar diffusion in removing magnetic fields \( (t_{MR} \ll t_{AD} \) in these regions).

Since magnetic fields are present in the cold clouds, the magnetic critical mass \( M_B \) should be considered, besides the Jeans mass, as a mass scale for star formation. We found that in outer part the cooling flow region \( (r \sim 100 \, \text{kpc}) \), \( M_B \) is low \( (\sim 10 \, M_{\odot}) \), so predicting an inefficient formation of massive stars over that region, in agreement with the absence of young star signature over the cooling flow region as a whole. In addition, in the innermost regions \( (r \sim 10 \, \text{kpc}) \) of the cooling flow, \( M_B \) reaches values close to the Galactic one, implying that the IMF is plausibly not very different from that in the solar neighbourhood, and, therefore, that massive stars are formed, as it is indicated by observations of young stars (type A or earlier) in the central regions of cooling flows. In this way, the variation of the biasing of the IMF with radius to the centre of the cooling flow in the right sense is reproduced by considering \( M_B \) as the mass scale regulating the star formation.
It should be mentioned that another process which can cause the star formation being concentrated in the inner regions of cooling flows is the interaction of radio jets with the ICM. In fact, imaging of central galaxies of cooling flows, including observations in the U-band (the most effective for studying blue stellar populations) reveals a variety of blue structure around the central galaxy (McNamara 1997). Four morphological types can be defined: unresolved point; disk; lobe; amorphous. The case for an association between radio sources and star formation is stronger for the lobe class, characterized by blue lobes of optical continuum located several kpc from the galaxy nucleus. The archetypes of this class, A1795 and A2597, have radio sources with bright lobes of blue continuum along the edges of their radio lobes (McNamara & O’Connell 1993; McNamara et al. 1996a,b). Several characteristics of the blue lobes support their origin in star formation: 1) the low blue polarization (McNamara et al. 1996b); 2) the absence of detailed correspondence between the blue lobes and the radio lobes; 3) HST images showing what appears to be blue star clusters along the edges of the radio lobes (McNamara et al. 1996a).

In the radio triggered star formation model, the radio jets collect pre-existent cold clouds along the edge lobes creating a gas overdensity which triggers or enhances star formation, which is located in the few central kpc of the cooling flow, where the jets are confined to. By contrast, in our model, the star formation occurs during the process of formation of cold clouds from perturbations arising from the hot phase of the cooling flow, but massive star formation is allowed only in the central region of the cooling flow. Within the classification scheme of McNamara (1997) for blue structures in cooling flows, the amorphous type, which encompasses most of the objects and which shows no obvious association with radio sources, could be explained by the model presented in this paper.

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