

Alfvén heating in optical filaments in cooling flows

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Abstract. One of the major problems concerning cooling flows is the nature of the mechanism powering the emission lines of the optical filaments seen in the inner regions of cooling flows. In this work we investigate the plausibility of Alfvén heating (AH) as a heating/excitation mechanism of optical filaments in cooling flows. We use a time-dependent hydrodynamical code to follow the evolution of cooling condensations arising from the 10^7 K cooling flow. The filaments contain magnetic fields and AH is at work at several degrees of efficiency (including no AH at all). We consider two damping mechanisms of Alfvén waves: nonlinear and turbulent. We calculate the optical line emission associated with the filaments and compare our results to the observations. We find that AH can be an important ionizing and heating source for class I filaments in the line-ratio scheme of Heckman et al. In addition, AH can be an important contributor to [OI] λ 6300 emission even for the more luminous class II systems.

Key words: magnetic fields – turbulence – galaxies: clusters – cooling flows – intergalactic medium – X-ray: galaxies – waves

1. Introduction

The short cooling times (less than a Hubble time) of the central intracluster medium (ICM) of X-ray emitting clusters of galaxies points to gas sinking towards the center of the cluster in a “cooling flow” (for reviews, see Fabian et al. 1984, 1991 and Fabian 1994). A sizeable proportion of the cooling flows also contains extended (from $\lesssim 1$ kpc to tens of kpc) optical emission line filaments around the central dominant galaxy of the cluster, which is always at the center of the flow (Heckman 1981; Cowie et al. 1983; Hu et al. 1985; Johnstone et al. 1987; Heckman et al. 1989; Baum 1992). These extended optical filaments systems are seen only in cooling flows and are thought to be a phase of the evolution of thermal instabilities arising in the cooling flow. The line emission flux ratio [NII] λ 6583/ $H\alpha$ allowed Heckman et al. (1989) to divide the filaments into two

distinct classes, class I with an average $\langle[\text{NII}]/H\alpha\rangle = 2.0$, and class II with $\langle[\text{NII}]/H\alpha\rangle = 0.9$. Also, the class II filament systems tend to have higher $H\alpha$ luminosity and to belong to cooling flows with greater mass accretion rates. More recently, however, the discovery of filaments in cooling flows whose line ratios are intermediate between those typical of class I and II systems (Crawford & Fabian 1992; Allen et al. 1992; Crawford et al. 1995) called for a continuous distribution instead of a clear split into two classes. In addition, there are some $H\alpha$ -luminous class I (i.e. with high [NII]/ $H\alpha$) systems (e.g., A1068, A2146, RX J0439.0+0520) departing from the trend of class I systems having low $H\alpha$ luminosities.

One of the major problems associated with the optical filaments is their high luminosities (typically $H\alpha$ luminosities are 10^{41} to 10^{42} ergs s^{-1}). Quiescently cooling gas that recombines only once at the X-ray determined mass accretion rate would not be detectable as emission line nebulae. The fact that the central regions of cooling flows often do show optical emission requires some source of energy to repeatedly reionize the gas. Several models, considering different mechanisms for ionization and heating of the gas, – shocks (David et al. 1988, David & Bregman 1989), thermal conduction (Böhringer & Fabian 1989), and photoionization by soft X-rays and EUV produced in the cooling gas (Voit & Donahue 1990; Donahue & Voit 1991; Voit et al. 1994) –, have met difficulties in explaining the observed line ratios and luminosities. It is possible that some combination of photoionization and shock models could explain the observations. One example of these hybrid models involves the combination of self-absorbed irradiating mixing layers of cold clouds embedded in the hot cooling gas and emission from shocks generated in collisions between these clouds (Crawford & Fabian 1992).

Jafelice and Friaça (1996) have investigated magnetic reconnection as a heating mechanism and concluded that magnetic reconnection cannot be invoked as the sole mechanism powering the optical line emission in cooling flows. However, it could be an important ingredient to explain the emission coming from low ionization lines. The models with high magnetic reconnection efficiencies exhibit a strong [OI] λ 6300 emission, and, therefore, magnetic reconnection could be an additional component together with other mechanisms producing most of

the emission in $H\alpha$ and higher ionization lines (as $[NII]\lambda 6583$). The existence of magnetic fields in the ICM has suggested magnetic reconnection as a heating mechanism. In this paper we investigate another heating mechanism expected to be at work in the presence of magnetic fields: Alfvén heating (AH). Here we explore the importance of AH not only as a dominant energy source for optical filaments in cooling flows but also as an ingredient contributing to the emission of some optical lines.

The Alfvén heating comes from the dissipation (damping) of Alfvén waves. These waves are easily generated in many cosmic plasmas, but they possess no linear damping mechanism since they are not compressive. Nonlinear damping of these waves occurs when one Alfvén wave decays into another plus a slow magnetosonic wave, or two Alfvén waves combine into one fast magnetosonic wave; the resulting magnetosonic waves can then be dissipated. The dissipation of these waves may contribute to heat the solar corona, to influence the interplanetary wave spectrum, and to determine the wave spectrum available to scatter cosmic rays. As they are not compressive, the nonlinear decay occurs due to second order effects in the wave amplitude. Interacting Alfvén waves are compressive and thus generate a new compressive wave (see Chin and Wentzel 1972). The resulting heating — at least in terms of nonlinear, resonance surface and turbulent damping mechanisms — has been applied to study the thermal stability in the broad line region of quasars and in the basis of the wind in hot stars, in a successful way (Gonçalves et al. 1993a, 1996a,b).

Alfvén waves are created by perturbed magnetic fields. In view of this, two conditions that are fulfilled by the core of a cooling flow make it a favorable site for the generation of Alfvén waves: it contains magnetic fields, and it is turbulent.

The lack of any strong hard X-ray emission due to inverse Compton from the relativistic electrons in a few clusters (generally not cooling flows) that have halo radio sources imposes a lower limit for the magnetic field of $0.1 \mu\text{G}$ over scales of up to 500 kpc (Rephaeli & Gruber 1988). At the smaller (~ 100 kpc) scales of cooling flows, magnetic fields of typically $1 - 3 \mu\text{G}$ are derived corresponding to a magnetic pressure of about 1% of the thermal pressure. At the center of a cooling flow still more intense magnetic fields must be present since the field is amplified by compression as the gas flows inward (Soker & Sarazin 1990). As a matter of fact, Faraday rotation and depolarization of the radio emission of extended radio sources (Ge & Owen 1993; Taylor et al. 1994) residing in cooling flows have revealed that the magnetic field increases inward and that it can reach 20–100 μG depending on the degree of ordering of the field. In this way, at the very center of the flow, the magnetic pressure can supersede the thermal pressure.

One kinematic signature of the filament systems is the lack of organized velocity patterns (e.g., rotation or shear or infall) (Heckman et al. 1989; Baum 1992). The filaments typically have very small rotational velocities and are turbulently, and not rotationally, supported. A small number of filament systems do show apparent rotation with rotational velocities of $\sim 300 \text{ km s}^{-1}$ within a few kpc. However, these same systems show disordered velocity patterns at larger scales (Hu et al. 1985). Lines

are broad throughout the filamentary region, but line widths decrease from 500–100 km s^{-1} in or near the galactic nucleus to 100–300 km s^{-1} at the largest radii (typically 5–15 kpc). This suggests that the inner ICM is highly turbulent, with the amplitude of random velocities increasing inward. In fact, the core of a cluster is expected to be turbulent not only due to the frequent crossing of galaxies through it but also due to relics of merging of subclusters. In addition, the absence of rotation in the center of cooling flows requires rotational breaking of the gas flowing inward, and turbulent viscosity is the most likely transport process of angular momentum in a cooling flow (Nulsen et al. 1984).

The possibility of using the turbulent energy to heat the plasma in the core of cooling flows was also considered by Loewenstein and Fabian (1990), in order to explain the kinematics of the cooling flow clouds. They assume a magnetic viscous heating process (‘plasma slip’) where the magnetic field that passes from the clouds to the hot gas can be forced to oscillate by the noise and so cause the ionized particles within the cloud to oscillate and collide with neutral particles. This process can efficiently transport Alfvén wave energy to length scales of $\sim 10^{17} \text{ cm}$.

2. Alfvén Heating in the Intracluster Medium

The emission line filaments have line widths of several hundred to $\sim 1000 \text{ km s}^{-1}$ (Heckman et al. 1989; Baum 1992; Crawford & Fabian 1992; Allen et al. 1992; Crawford et al. 1995). It is possible that these velocities of the filaments are turbulent and that the hot component of the ICM is itself turbulent. Anyway, there is plenty of kinetic energy to be tapped via Alfvén waves into an energy source for the ionization of the filaments. Several damping mechanisms can be responsible for Alfvén heating. In this work we consider the nonlinear damping and the turbulent damping for Alfvén waves.

The damping mechanisms above have been investigated before in many astrophysical objects: late-type stars, protostellar and solar winds (Jatenco-Pereira & Opher 1989a,b,c); galactic and extragalactic jets (Opher & Pereira 1986; Gonçalves et al. 1993b); early-type stars (dos Santos et al. 1993); broad line regions of quasars (Gonçalves et al. 1993a, 1996a) and others.

2.1. Nonlinear damping

An Alfvén wave is likely to dissipate because of its nonlinear interaction with either the non-uniform ambient field or another Alfvén wave (Wentzel 1974). The nonlinear interaction of magnetohydrodynamic waves has been treated in detail by Kaburaki & Uchida (1971), Chin & Wentzel (1972), and Uchida & Kaburaki (1974). When the magnetic field is weak, i.e. when the Alfvén velocity v_A is lower than the sound velocity c_s , it is found that two Alfvén waves travelling in opposite directions along a magnetic field line can couple nonlinearly to give an acoustic wave, which in turn dissipates relatively quickly. In regions of strong ($v_A > c_s$) magnetic field, one Alfvén wave can decay into another Alfvén wave and a

sound wave travelling in the opposite direction. The resulting Alfvén wave has a frequency smaller than the original one and it can, in turn, decay into another lower-frequency Alfvén wave plus an acoustic wave. The cascade continues until all the Alfvénic energy has been converted to acoustic waves that dissipate rapidly. The latter possibility is considered in this paper. In our models, the onset of nonlinear heating occurs for $\beta = P_B/P_{gas} = (B^2/8\pi)/nk_B T > \beta_{on} > 1$, where β_{on} is the initial value of β when AH becomes important ($\beta > 1$ corresponds to $v_A/c_s > \sqrt{6/5}$ for an ideal $\gamma = 5/3$ gas). Note that, following the convention widely used in cooling flow studies, we define $\beta = P_B/P_{gas}$, whereas in plasma physics, $\beta_{pl} = P_{gas}/P_B$ denotes the “beta parameter” of the plasma.

According to Lagage & Cesarsky (1983), the nonlinear damping rate is

$$\Gamma_{NL} = \frac{1}{4} \sqrt{\frac{\pi}{2}} \xi \bar{\omega} \left(\frac{c_s}{v_A} \right) \frac{\rho \langle \delta v^2 \rangle}{B^2/8\pi}, \quad (1)$$

where $\xi = 5 - 10$, c_s is the sound velocity, v_A the Alfvén velocity, $\bar{\omega}$ a characteristic Alfvén frequency and $\rho \langle \delta v^2 \rangle / (B^2/8\pi)$ the ratio of the energy density of Alfvén waves to that of the magnetic field. As we are interested in AH coming from the nonlinear damping of Alfvén waves, we heuristically derive the dependences of the heating rate H_{NL} ($\text{erg cm}^{-3} \text{ s}^{-1}$) with density and temperature. Thus, the nonlinear Alfvénic heating is:

$$H_{NL} = \frac{\Phi_w \Gamma_{NL}}{v_A}, \quad (2)$$

where Φ_w is the wave flux, Γ_{NL} is given by (1), and $v_A = B/\sqrt{4\pi\rho}$ is the Alfvén velocity. As our perturbation collapses, the component of the magnetic field perpendicular to the direction of compression is amplified. For our plane parallel geometry, $B \propto A^{-1} \propto \rho$, where A is the cross-sectional area perpendicular to the magnetic field. As a consequence, $v_A \propto \rho^{1/2}$. Let the dependence of Φ_w on ρ be given as $\Phi_w \propto \rho^c$. Taking $\Phi_w = \rho \langle \delta v^2 \rangle v_A$, we have $\rho \langle \delta v^2 \rangle \propto \rho^{c-1/2}$. Since $c_s \propto T^{1/2}$, for $\bar{\omega}$ independent of the density, we obtain:

$$H_{NL} \propto \rho^{2c-7/2} T^{1/2}. \quad (3)$$

For a plane-parallel geometry, $\Phi_w \propto A^{-1} \propto \rho$, implying $c = 1$, and Eq. (3) becomes:

$$H_{NL} \propto \rho^{-3/2} T^{1/2}. \quad (4)$$

2.2. Turbulent Damping

Turbulence theory indicates that the spectrum of turbulent Alfvén waves has a power law dependence in phase space

$$P(k) \propto k^{-\beta},$$

where k is the Alfvén wavenumber, β is the spectral index, and

$$\int P(k) 4\pi k^2 dk$$

is the energy density of turbulent Alfvén waves. The value of the spectral index is determined by the type of the turbulence (De Groot & Katz 1973; Kainer et al. 1972; Eilek & Henriksen 1984).

Tu et al. (1984) noted that the nonlinear interaction between outward and inward propagating waves results in an energy cascading process. A small part of the energy of lower frequency fluctuations cascades to higher frequency fluctuations until it reaches a frequency high enough for some dissipation process to occur, the most probable candidate being proton-cyclotron damping.

As noted by Hollweg (1987), the observed magnetic power spectra, P_B , in the solar wind exhibits a well-developed inertial subrange resembling Kolmogorov turbulence, i.e. $P_B \propto k^{-5/3}$, over more than 3 orders of magnitude of k (Matthaeus & Goldstein 1982). This indicates a cascade to small scales. The turbulent cascade transfers wave energy from large to short scales, and, in the end, the dissipation of energy through turbulence is governed by the small scale linear absorption mechanism. Exploiting the similarity of $P_B \propto k^{-5/3}$ and Kolmogorov turbulence in ordinary fluids, the volumetric heating rate associated with the cascade process can be written as

$$H_T = \rho \langle \delta v^2 \rangle^{3/2} / L_{\text{corr}}, \quad (5)$$

where ρ is the mass density, $\langle \delta v^2 \rangle$ is the velocity variance associated with the field, and L_{corr} is a measure of the transverse correlation length (Hollweg 1986, 1987).

As in the previous subsection, we can derive the dependence of the turbulent heating rate on ρ . For a plane parallel geometry, $\langle \delta v^2 \rangle \propto \rho^{c-3/2}$ (assuming $\Phi_w \propto \rho^c$), and adopting $L_{\text{corr}} \propto \rho^b$, we obtain:

$$H_T \propto \rho^{(3/2)c-b-5/4}. \quad (6)$$

For a plane parallel geometry, $c = 1$ ($\Phi_w \propto \rho$), and, if we assume that $L_{\text{corr}} \propto B^{-1/2}$ (Hollweg 1986, 1987), then $b = -1/2$ (since $B \propto \rho$). The resulting turbulent Alfvén wave heating is

$$H_T \propto \rho^{3/4}. \quad (7)$$

3. Time-dependent Models for Cooling Condensations

We have investigated the evolution of optical filaments since their formation out of the hot phase of the cooling flow and calculated their optical signature within the scenario outlined in Sect. 2.

The evolution of the cooling filaments is obtained by solving the hydrodynamical equations of mass, momentum and energy conservation (see Friaça 1986,1993; Friaça & Terlevich 1994,1996). The condensations are assumed to be self-gravitating. Since there is no 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 an isochoric 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. We have chosen an isochoric cooling function because the evolution of the gas is nearly isochoric as soon as the gas cools below 10^6 K, first due to the rapid cooling for temperatures around the peak ($T \sim 10^5$ K) of the cooling function, and then due to the magnetic support against further compression of the gas at lower 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 (Grunewald & Viegas 1992). The adopted abundances are half-solar, as derived from X-ray spectroscopy of the ICM. (Solar abundances are from Grevesse & Anders 1989.)

The initial density perturbations are characterized by an amplitude A and a length scale L , following $\delta\rho/\rho = A \sin(x)/x$ (here $x = 2\pi r/L$). We have also assumed a plane-parallel geometry and that the perturbations are isobaric and nonlinear ($A = 1$). The geometry is justified by the fact that the 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 (see Sect. 5). An unperturbed $n_H = 0.1 \text{ cm}^{-3}$ and $T = 10^7$ K is assumed for the filament, appropriate for the inner regions of a cooling flow, where the filaments are more often seen. 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 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.

Here we investigate several representative models with magnetic fields, one with no AH and the others with AH for two damping mechanisms (nonlinear and turbulent) and at different efficiencies (see Table 1). Model A allows for the presence of a magnetic field only through a magnetic pressure term ($P_B = B^2/8\pi$) in the equation of motion. It gives the benchmark to evaluate the effects of AH. In models B to F, the energy equation include AH as an additional heating term, which is turned on only for $\beta > \beta_{on}$, where β_{on} is the value of β when AH becomes important. We considered nonlinear and turbulent Alfvén wave heating. From Eqs. (4) and (7), the heating term has the form

$$H_{NL} = \zeta H_0 (n/n_0)^{-3/2} (T/T_0)^{1/2}, \quad (8)$$

for nonlinear heating, and

$$H_T = \zeta H_0 (n/n_0)^{3/4}, \quad (9)$$

for turbulent heating, where ζ is the efficiency of Alfvén heating. The choice of the normalizations is the following: 1) $T_0 = 10^5$ K (the temperature at which optical emission begins to be important); 2) $n_0 = 3.267 \times 0.1 \text{ cm}^{-3}$, where 3.267 is the compression factor from the unperturbed $n_H = 0.1 \text{ cm}^{-3}$ and $T = 10^7$

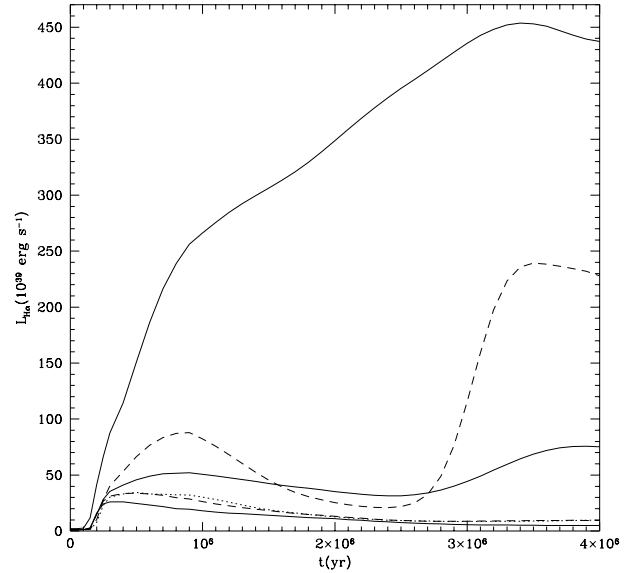


Fig. 1. Evolution of $\tilde{L}_{H\alpha}$, the normalized H α luminosity (for its definition see the text), for the models A-C (solid lines), D (dotted line) and E-F (dashed lines); the curves are displaced upwards for increasing values of ζ .

K initial state, to $T = T_0$, under isobaric conditions; and 3) $H_0 = (3/2) nk_B T/t_{col} = 2.55 \times 10^{-24} \text{ erg s}^{-1} \text{ cm}^{-3}$, where t_{col} is the collapse time (defined below) for the filament with no heating.

4. Results

In order to assess the importance of the optical emission, a number of quantities characterizing the optical phase of our models are presented in Table 1: the collapse time t_{col} is the time elapsed since the beginning of the calculations until the beginning of the optical phase; $\tilde{L}_{H\alpha,max}$ is the maximum luminosity in H α ; t_{max} is the time when $\tilde{L}_{H\alpha,max}$ is attained; $t_{1/2}$ is the time when half the mass of the perturbation has cooled below $T = 5 \times 10^5$ K; (t_{max} and $t_{1/2}$ are counted from the beginning of the optical phase); and $\tilde{L}_{H\alpha,ave}$ is the average luminosity since the beginning of the optical phase until $t_{1/2}$. The luminosity $\tilde{L}_{H\alpha}$ is normalized to $\dot{M} = 100 M_\odot \text{ yr}^{-1}$, with \dot{M} taken as equal to the ratio of the mass of the condensation to its collapse time.

At the beginning of the growth 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 a 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 β becomes > 1 . At this stage, the magnetic pressure halts further compression, while the temperature keeps dropping (if no heating mechanism is efficient enough to prevent the gas from cooling). When the temperature has decreased enough, the gas begins to emit optical lines. We consider the beginning of the phase of optical line emission when the temperature of the innermost cell

Table 1. Properties of models.

Model	Heating	ζ	β_{on}	t_{col} (10^6 yr)	t_{max} (10^6 yr)	$t_{1/2}$ (10^6 yr)	$\tilde{L}_{H\alpha,max}$ (10^{40} erg s $^{-1}$)	$\tilde{L}_{H\alpha,ave}$ (10^{40} erg s $^{-1}$)
A	none	0.	–	6.00	0.345	4.51	2.65	1.08
B	turbulent	1.	1.	7.36	4.56	4.10	39.8	27.1
C	turbulent	0.3	1.	6.24	0.686	4.51	4.30	2.81
D	nonlinear	0.3	3.	6.16	0.467	4.41	3.19	1.44
E	nonlinear	1.	10.	6.00	3.67	4.51	20.9	7.70
F	nonlinear	0.3	10.	6.00	0.447	4.51	3.20	1.40

(i.e. the first cell to cool) falls below 5×10^5 K. Before this temperature has been reached, the gas is in its X-ray phase, during which most of the cooling occurs via EUV and X-ray lines. The collapse time is the smallest (6×10^6 yr) for models with no heating (model A) or for those in which the heating is turned on later in the evolution of the perturbation (models E and F). As the heating becomes more important during the X-ray phase, the collapse is delayed (i.e. t_{col} is increased). Model B (turbulent heating and $\zeta = 1$) is the slowest to collapse. A model with nonlinear heating, $\beta_{on} = 3$, and $\zeta = 1$, has been run, but its mass that reaches $T < 5 \times 10^5$ K is at most 35% of the total mass of the perturbation. This result suggests that nonlinear Alfvén heating can constitute a mechanism for suppressing the growth of thermal instabilities in cooling flows.

The nonlinear and the turbulent AH's represent extreme opposite dependencies of AH on density. Turbulent AH ($H_T \propto n^{3/4}$) deposits more energy at the center of the filament, where the density is higher. On the other hand, nonlinear AH ($H_{NL} \propto n^{-3/2}T^{1/2}$) deposits more energy per unit volume in the outer regions of the filaments, where the density is lower. However, due to magnetic support, the central density of the cooled filament ($T \approx 10^4$ K) is only ≈ 3.3 times the initial unperturbed density, and the central decrease of the AH rate due to density variation amounts to only a factor 6. In the end, the fact that the energy is deposited in a much cooler gas at the center than on the outside of the filament ($T \approx 10^7$ K) makes the AH somewhat more important in the colder, central gas than in the outer skin of the filament, as we can see from the timescale for heating $t_H = (3/2)nk_B T/H_{NL} \propto n^{5/2}T^{1/2}$, which is 1.6 times smaller at the center than on the outside of the filament. The inverse dependency of H_{NL} on the density explains the suppression of the growth of the perturbation in the model with non-linear heating, $\zeta = 1$ and $\beta_{on} = 3$. It should be noted that in our calculations, we assume that the filaments are optically thin to Alfvén waves, so that energy is deposited by AH throughout the filament.

The evolution of $\tilde{L}_{H\alpha}$ is shown in Fig. 1. and the evolution of the line ratios can be followed in the diagram [NII] $\lambda 6583/H\alpha$ versus [OI] $\lambda 6300/H\alpha$ (Fig. 2). For a model to be successful, it should not only reproduce the position of the filaments in the line ratio diagrams but also account for their luminosity. The models B (turbulent heating) and E (nonlinear heating) are the more energetically promising. The energy budget requirements

of class I filaments are satisfied (see Table 1 and Fig. 1) since the class I objects are the less luminous systems (an average $\langle \tilde{L}_{H\alpha} \rangle = 4 \times 10^{40}$ erg s $^{-1}$). Our models even fulfill the luminosity requirements for some of the less luminous class II filaments, with an average $\langle \tilde{L}_{H\alpha} \rangle = 3 \times 10^{41}$ erg s $^{-1}$ (Heckman et al. 1989). The luminosity of our models, however, fall short of the most luminous class II systems (e.g. Perseus), so that we propose the AH as the mechanism powering primarily class I filaments. From the [NII]/H α versus [OI]/H α diagram, the model B (with turbulent heating) reproduces the values of [OI]/H α of the filaments, but somewhat overproduces [NII] $\lambda 6584$ emission of class I filaments. On the other hand, model E (with nonlinear heating) reproduces the values of [NII]/H α , but overproduces [OI] $\lambda 6300$ emission. It seems that if some combination of these mechanisms is at work, a range of heating efficiencies and chemical abundances could account for the loci of class I systems in the [NII]/H α versus [OI]/H α diagram.

5. Conclusions

From the energetic viewpoint, our models could account for typical filament systems with $H_{rec} \approx 10 - 100$ but not for the extreme ones (e.g., Perseus) with $H_{rec} \approx 1000$ (H_{rec} is the number of recombinations per cooling proton required to yield the observed H α luminosity). Our models are better at reproducing the luminosities of the weaker class I filaments than the more luminous class II systems. AH could be a dominant heating mechanism for the class I filaments, and even for the less luminous class II filaments.

It should be noted that there are evidences that matter is dropping out of the cooling flows at radii larger than $r \sim 10$ kpc, so that only a fraction of the overall cooling flow rate (over typical radii of ~ 100 kpc) reaches the region where the filaments are seen. A fraction $\phi \approx 0.1$ reaching $r \sim 10$ kpc is suggested from a $\dot{M} \propto r$ variation (Thomas et al. 1987). This value is derived from a simple model in which the flow is stationary and the X-ray emission comes from a homogeneous gas. Taking into account nonsteady flow (the flow time from 100 to 10 kpc is comparable to the age of the system — for instance, the values of n and T adopted in the present calculations imply a flow velocity of $5 - 50$ km s $^{-1}$ at 10 kpc for $\dot{M} = 10 - 100 M_{\odot}$ yr $^{-1}$) and the contribution of nonlinear blobs to the X-ray emission makes the reduction of \dot{M} less drastic than that given

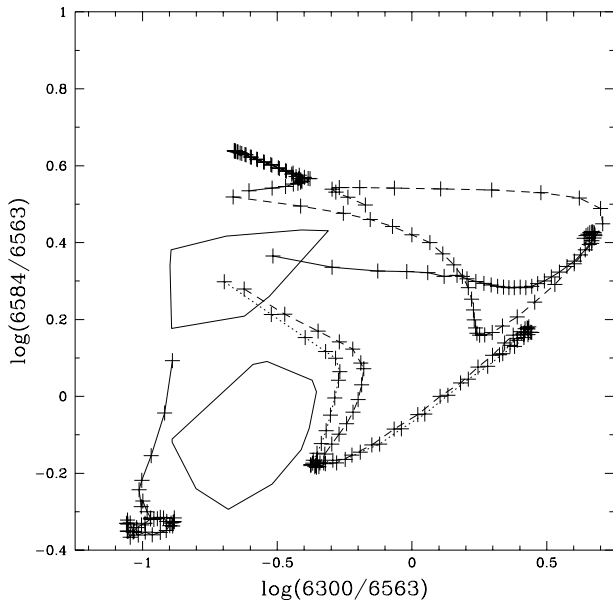


Fig. 2. Evolution of [NII]/H α versus [OI]/H α for the models A-C (solid lines), D (dotted line) and E-F (dashed lines); the curves are displaced upwards for increasing values of ζ . The plus signs on the curves indicate the elapsed times (starting on the left) since the beginning of the optical emission phase: 2×10^5 , 2.5×10^5 , 3×10^5 yr, and from then on in intervals of 10^5 yr until 4×10^6 yr. The contours enclose the data points of Heckman et al. (1989). Note the clear separation between filaments of class I and II.

by the $\dot{M} \propto r$ model (Meiksin 1990; Friaça 1993). These effects, however, do not prevent matter from being removed from the flow, and the resulting ϕ is $\approx 0.2 - 0.3$. Therefore, mass removal from the cooling flow limits the energetic input of AH, and the luminosities given in the previous section should be reduced by a factor ϕ .

Even if AH cannot be invoked as the sole mechanism powering the optical line emission of class II filaments, it could be, however, an important ingredient to explain the emission coming from low ionization lines in these systems. The models with nonlinear heating and high AH efficiencies exhibit a strong [OI] λ 6300 emission, and, therefore, AH could be an additional component together with other mechanisms for producing most of the emission in H α and higher ionization lines (as [NII] λ 6583).

The combination of two distinct heating mechanisms, each one being responsible for certain emission lines and/or explaining one class of filaments, has allowed to build hybrid models for optical filaments, which have been particularly successful at reproducing the observations of optical filaments. Shocks models tend to reproduce the locus in the line-ratio diagram of class II filaments, although the energetic requirements are stringent. A hybrid model could, therefore, combine shocks and an additional heating source which explains the higher ionization class I filaments. In this way, Crawford & Fabian (1992) invoke shocks between cold clouds to explain the class II filaments (and produce their [OI] emission) and mixing layers to

account for the class I filaments with lower H α luminosities and higher levels of ionization (higher [NII] λ 6583/H α ratios). Other additional heating sources are magnetic reconnection (Jafelice & Friaça 1996), and Alfvén heating (this work). Jafelice and Friaça (1996) suggest a hybrid model involving magnetic reconnection (with an efficient production of [OI] emission), and self-absorbed mixing layers with high flux and low temperature for the incident radiation (producing most of the H α and [NII] emission).

Whether AH is at work together with shocks or with mixing layers, it efficiently supplies [OI] emission. For a representative $\dot{L}_{H\alpha} = 1 \times 10^{41} \phi \text{ erg s}^{-1}$ of model E, one obtains a [OI] λ 6300 luminosity $\approx 2 \times 10^{41} \phi \text{ erg s}^{-1}$ (see Fig. 2). Given the average ratio [OI] λ 6300/H α = 0.25 of the optical filaments, AH could account for the [OI] λ 6300 emission of systems with $\dot{L}_{H\alpha}$ up to $\approx 8 \times 10^{41} \phi \text{ erg s}^{-1}$. The AH keeps the gas relatively warm, giving rise to strong emission of [OI] λ 6300.

We note that the energetic requirements concerning the [OI] emission of the more luminous systems, like Perseus, with $\dot{L}_{H\alpha} = 2.6 \times 10^{42} \text{ erg s}^{-1}$ (considering a H α luminosity of $4.7 \times 10^{42} \text{ erg s}^{-1}$ (Heckman et al. 1989) and a cooling flow rate of $183 M_{\odot} \text{ yr}^{-1}$ (Fabian 1994)), are not satisfied by our model even in the most favorable case. For these extreme systems, an additional heating mechanism is required.

Whereas there is undoubtedly a connection between cooling flows and optical filaments, this connection is troubled by some facts, and our model can shed light in this issue. In the first place, while there is a strong correlation between the H α luminosity and the mass accretion rate (at a 99.94% confidence level according to Heckman et al. 1989), the relation cannot be direct because of the large (more than two orders of magnitude) scatter in the relation $L_{H\alpha} - \dot{M}$ and the fact that some massive cooling flows (e.g., A2029) show no detectable line emission. The existence of a cooling flow, therefore, is a necessary but not sufficient condition for detectable line emission. Secondly, except for a few filament systems (e.g., Perseus and A1795) extending over several tens of kpc, the optical line emission is confined to the inner 10 kpc of cooling flows, whereas the X-ray images of clusters reveal that the cooling gas is distributed throughout the cooling radius (~ 100 kpc).

The high spatial concentration of optical filaments towards the center could be explained by a greater magnetic field strength in the central regions (Soker & Sarazin 1990) and by a higher level of turbulence in these regions (Loewenstein & Fabian 1990; Lowenstein 1990; Begelman & Fabian 1990). As a consequence, an intense Alfvén wave generation is boosted only in the inner cooling flow. On the other hand, the level of turbulence could be the “second parameter” besides mass accretion rate, regulating the luminosity of optical filament systems. Turbulence, caused, for instance, by stirring of the central ICM by a galaxy moving through the cluster core, or by interactions between the ICM and the relativistic plasma of an extended radio source, could trigger, via generation and dissipation of Alfvén waves, optical emission lines. In this scenario, the generation of Alfvén constitutes a step in the tapping of the turbulent energy of the ICM into line luminosity.

Additional support for the idea that turbulence can be crucial for producing the line luminosity comes from the fact that the kinetic energy flow, determined from the observed velocity dispersion of the filaments, correlates much tighter (a scatter of one order of magnitude) with the $H\alpha$ luminosity (Heckman et al. 1989) than \dot{M} does. This indicates that it is the combination of mass flow and high levels of turbulence that is relevant for the line luminosity, rather than a large mass accretion rate alone.

The present calculations are intended to apply to the inner ~ 10 kpc of the cooling flows, where the optical filaments are most commonly seen. The turbulent velocities of the cooling flow increase toward the center of the cluster, as inferred from the increase of the line widths near the center (Heckman et al. 1989). Since the turbulent energy of the cooling flow is the energy source of the Alfvén waves, it is only in the inner ~ 10 kpc that the density of turbulent energy is high enough to make AH efficient. In this region, blobs condensating out of the cooling flow are kept warm enough by AH to produce strong line emission. Blobs cooling down in the outer regions are subject to low levels of AH and cool quiescently without noticeable optical emission (similarly to model A). In this way, the AH mechanism is consistent with the fact that line emission does not extend to ~ 100 kpc.

A further issue raised by the results of our models concerns the growth of thermal instabilities in cooling flows. It has been suggested that a number of processes could inhibit the growth of thermal instabilities in the presence of gravitational fields and background flow in cooling flows (Malagoli et al. 1987; Balbus 1988; Balbus & Soker 1989; Tribble 1989; Loewenstein 1989; Brinkmann et al. 1990; Hattori & Habe 1990; Yoshida et al. 1991; Malagoli et al. 1990; Reale et al. 1991). The fact that one of our models (with nonlinear heating, $\beta_{on} = 3$, and $\zeta = 1$) has reached thermal stability shows that also Alfvén heating can constitute a mechanism for suppressing strong growth of thermal instabilities in cooling flows. On the other hand, Gonçalves et al. (1993a; 1996a) have considered the possibility that the broad line regions of quasars are formed via thermal instability in the presence of AH. They have investigated three damping mechanisms of Alfvén waves – resonance surface, nonlinear, and turbulent –, and found that AH could establish a stable two-phase medium in the broad line regions of quasars. The thermal stability of the model mentioned above suggests that, also in the case of the cooling flow medium, AH could induce a stable two-phase equilibrium.

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