

CHANDRA ESTIMATE OF THE MAGNETIC FIELD STRENGTH NEAR THE COLD FRONT IN A3667

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ABSTRACT

We use the *Chandra* observation of the cold front in the intracluster gas of A3667 to estimate the magnetic field strength near the front. The front is seen in the *Chandra* data as a sharp discontinuity in the gas density which delineates a large body of dense cool gas moving with the near-sonic velocity through the less dense, hotter gas. Without a magnetic field, the front should be quickly disturbed by the Kelvin-Helmholtz instability arising from tangential motion of gas layers. However, *Chandra* image shows that the front is stable within a $\pm 30^\circ$ sector in the direction of the cloud motion, beyond which it gradually disappears. We suggest that the Kelvin-Helmholtz instability within the $\pm 30^\circ$ sector is suppressed by surface tension of the magnetic field whose field lines are parallel to the front. The required field strength is $B \sim 10 \mu\text{G}$. Magnetic field near the front is expected to be stronger and have very different structure compared to the bulk of the intergalactic medium, because the field lines are stretched by the tangential gas motions. Such a magnetic configuration, once formed, would effectively stop the plasma diffusion and heat conduction across the front, and may inhibit gas mixing during the subcluster merger. We note that even the increased magnetic field near the front contributes only 10–20% to the total gas pressure, and therefore magnetic pressure is unimportant for hydrostatic cluster mass estimates.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (A3667) — magnetic fields — X-rays: galaxies

1. INTRODUCTION

Magnetic fields can profoundly affect the properties of the intergalactic medium in clusters. Examples include suppression of heat conduction, which is required to maintain the cluster cooling flows (see the review by Fabian 1994), and a possibility of a dynamically significant magnetic pressure to explain the difference between the X-ray and strong lensing cluster mass estimates (Loeb & Mao 1994, Miralda-Escudé & Babul 1995). So far, intracluster magnetic fields were measured by Faraday rotation in radio sources seen through the IGM (e.g., Kim, Kronberg & Tribble 1991), or by combining radio and hard X-ray data on cluster radio halos under the assumption that the X-rays are produced by inverse Compton scattering of the microwave background (e.g., Fusco-Femiano et al. 2000). Both these methods indicate the magnetic field strength on the microgauss level, with considerable uncertainty. In this Paper, we apply a completely new approach that uses the effect of the magnetic field on the dynamics of the intracluster plasma.

Chandra recently revealed that in at least two clusters, A2142 (Markevitch et al. 2000) and A3667 (Vikhlinin, Markevitch & Murray 2000, Paper I hereafter), the dense cool cores are moving with high velocity through the hotter, less dense surrounding gas. In both cases, the cool gas is separated from the hotter ambient gas by a sharp density discontinuity, or a “cold front”. A similar structure appears to be observed in RXJ1720.1+2638 (Mazzotta et al. 2000), although the temperature data for that cluster are less accurate. In Paper I, we have shown that the cool gas cloud in A3667 moves with a near-sonic velocity in the ambient hot gas. While the speed of the cloud in A2142 cannot be measured accurately, its value is consistent with velocities up to the velocity of sound.

A strong suppression of the transport processes, most probably by magnetic fields, is required to prevent the observed sharp

density and temperature gradients from dissipating. Ettori & Fabian (2000) argue that the sharp change of gas temperature in A2142 requires a very significant suppression of heat conduction relative to the classical value. In A3667, the suppression of diffusion is observed directly, because the width of the density discontinuity is smaller than the Coulomb mean free path (Paper I).

In both A3667 and A2142, the cold front appears to be dynamically stable because it has a smooth shape and shows no visible perturbations within a certain sector in the apparent direction of the cloud motion. In this Paper, we use this fact to infer the strength of the intracluster magnetic field that could naturally provide surface tension stabilizing the front against the development of the Kelvin-Helmholtz instability.

We use $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The derived magnetic field strength scales as $h^{1/4}$, while the derived ratio of magnetic and thermal pressures does not depend on H_0 .

2. OVERVIEW OF CHANDRA RESULTS

The full account of the *Chandra* observation of A3667 is given in Paper I, and here we briefly review the relevant details. The most prominent feature in the *Chandra* image is the sharp 0.5 Mpc-long discontinuity in the surface brightness distribution located approximately 550 kpc South-East of the cluster center (Fig. 1). The gas temperature distribution shows unambiguously that this structure is a boundary between the large dense body of cool ($T_c = 4.1 \pm 0.2 \text{ keV}$, 68% confidence) gas moving through the hotter ($T_h = 7.7 \pm 0.8 \text{ keV}$) ambient gas. We call this structure the “cold front”. The front shape in projection is very accurately described by a circle with $R = 410 \pm 15 \text{ kpc}$.

The gas pressure profile across the front shows that the cloud moves at a speed close to the velocity of sound in the ambient hot gas (with the Mach number $M = 1 \pm 0.2$). The measured high velocity of the cloud is substantiated by the observed com-

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pression of the ambient gas near the front, and a possible bow shock seen in the *Chandra* image further ahead of the front. This moving cloud probably is a remnant of one of the large subclusters that have merged recently to form the A3667 cluster.

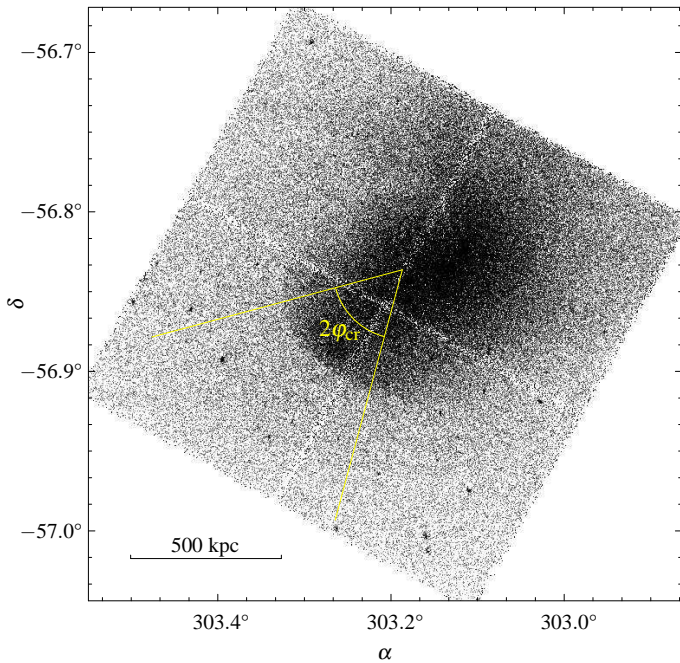


FIG. 1.— *Chandra* 0.5–4 keV image of A3667. The surface brightness edge (cold front) is sharp within the sector $2\varphi_{\text{cr}} = 60^\circ$, outside which it gradually disappears.

3. MAGNETIC FIELD AND THE STRUCTURE OF THE FRONT

The observed width of the front is very small. Even with the *Chandra* resolution, the surface brightness profile across the front is consistent with projection of an infinitely narrow gas density discontinuity. The upper limit on its width, $3.5''$ or 5 kpc, is 2–3 times smaller than the Coulomb mean free path (Paper I). This requires suppression of the diffusion by a magnetic field. A magnetic configuration which can stop the diffusion should indeed arise in a narrow boundary region between the two tangentially moving gas layers, through a process schematically shown in Fig. 2. As the ambient gas flows around the dense cloud and the cool gas is stripped from the surface of the cloud, magnetic field lines, which are frozen into the gas and initially tangled, should stretch along the front. When a layer with the parallel magnetic field forms, it would prevent further stripping of the cool gas and also stop microscopic transport processes across the boundary, explaining the observed small width of the front.

Such a layer with the parallel magnetic field also would support the dynamical stability of the front. At some distance from the leading edge of the cloud, the gas exterior to the front should develop a high tangential velocity. The interface between the tangentially moving gas layers normally is unstable due to the Kelvin-Helmholtz (K-H) instability. We show below that in the absence of any stabilizing factors, the K-H instability should disturb the front surface outside $\sim 10^\circ$ of the direction of the cloud motion. Figure 1 shows that the front has a smooth circular shape and remains sharp within the sector $\varphi_{\text{cr}} \approx 30^\circ$ in the direction of motion, and hence should be dynamically stable.

We suggest that the K-H instability is suppressed by surface tension of the frozen-in magnetic field, provided that it is parallel to the front. At larger angles ($\varphi > 30^\circ$) from the direction of motion, the front becomes less sharp and gradually vanishes. We interpret this as the onset of the K-H instability, when the tangential velocity of the ambient gas exceeds a critical value beyond which the instability cannot be suppressed by the magnetic field (cf. Fig. 2b). Assuming that the interface between two gases is barely unstable at $\varphi = 30^\circ$, we can estimate the required magnetic field strength.

Our further discussion is organized as follows. In § 4, we estimate the distribution of the tangential velocity of the ambient gas near the leading edge of the cloud. In § 5, we demonstrate that if the Kelvin-Helmholtz instability is not suppressed, its growth time is smaller than the cluster core passage time for angles $\varphi > 10^\circ$, and therefore the instability already should have disturbed the front. In § 6, we estimate the magnetic field strength from the condition that the Kelvin-Helmholtz instability is suppressed within the sector $\varphi < \varphi_{\text{cr}}$, but develops at larger angles.

For simplicity, we assume that the front moves through the ambient gas with the Mach number $M = 1$ exactly (while the measured value is $M = 1 \pm 0.2$).

4. TANGENTIAL VELOCITY ALONG THE FRONT SURFACE

For our purposes, the 3D shape of the cloud can be approximated by a cylinder with a ~ 250 kpc radius that has a rounded head with the curvature radius $R = 410$ kpc seen as a front in projection. The radius of the region of interest (an area on the front within $\varphi \lesssim 30^\circ$) is smaller than the radius of the cylinder. Therefore, we can adequately approximate the gas flow in this region by that around a ($R = 410$ kpc) sphere, for which there are published laboratory measurements and numerical simulations for a range of Mach numbers of the inflowing gas.

It is instructive to consider first the analytic solution for the flow of an incompressible fluid (e.g., Lamb 1945, see also Fig. 2b). The inflowing gas slows down near the stagnation point at the leading edge of the sphere but then reaccelerates to high velocities as it is squeezed to the sides by new portions of the inflowing gas. The velocity at the surface of the sphere has only a tangential component, $V_t = \frac{3}{2}V_\infty \sin \varphi$, where V_∞ is the velocity of the inflowing gas at infinity. Already at $\varphi = 30^\circ$, the incompressible gas has $V_t = \frac{3}{4}V_\infty$.

There is no known analytic solutions for the flow of compressible gas around a sphere at $M \approx 1$, but the qualitative picture is similar. We use the results of numerical simulations of the $M_\infty = 1.05$ flow by Rizzi (1980), whose results are in good agreement with the published laboratory measurements at slightly higher M_∞ (e.g., Gooderman & Wood 1950). The velocity field of a compressible gas flow is parameterized by the spatial distribution of the local Mach number. The distribution of the Mach number on the surface of the sphere derived from Rizzi's simulation can be approximated as

$$M \simeq 1.1 \sin \varphi. \quad (1)$$

At $\varphi = 30^\circ$, the local Mach number is $M = 0.55$. In absolute units, the gas velocity at this point is $V = 0.61 V_\infty$, i.e. only 20% lower than that in the incompressible solution.

5. KELVIN-HELMHOLTZ INSTABILITY WITHOUT MAGNETIC FIELD

Consider the flat interface between cold gas at rest and a hotter gas flowing at the local Mach number M . The velocity of

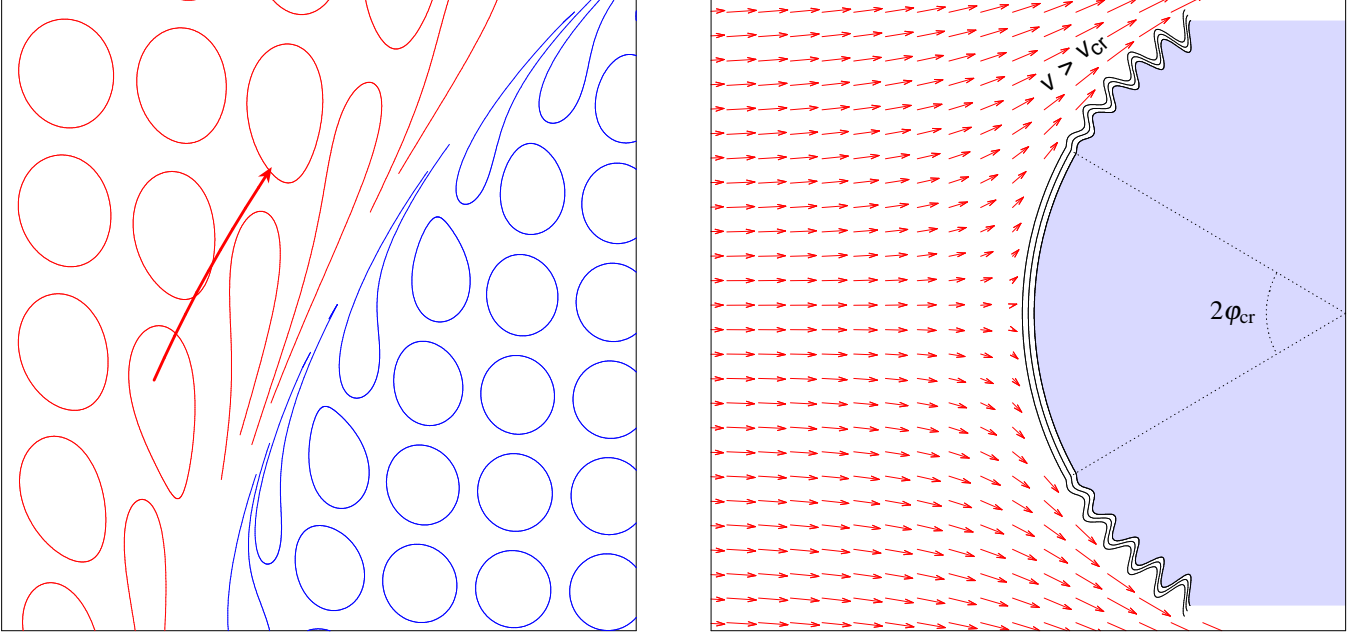


FIG. 2.— (a) Illustration of the formation of the magnetic layer near the front surface. The initially tangled magnetic lines in the ambient hot gas (red) are stretched along the surface because of tangential motion of the gas. The magnetic lines inside the front are stretched because, in the absence of complete magnetic isolation, the cool gas experiences stripping. This process can form a narrow layer in which the magnetic field is parallel to the front surface. Such a layer would stop the transport processes across the front, as well as further stripping of the cool gas. (b) The interface between the cool and hot gas is subject to the Kelvin-Helmholtz instability. The magnetic layer can suppress this instability in the region where the tangential velocity is smaller than a critical value V_{cr} . The velocity field shown for illustration corresponds to the flow of incompressible fluid around a sphere.

the flow can be sufficiently large so that the compressibility of the gas is important. In the absence of stabilizing factors such as gravity or surface tension, the interface is unstable due to the Kelvin-Helmholtz instability (see, e.g., Gerwin 1968 for a review). The wave vector of the fastest-growing mode is in the direction of the flow. The growth time of this mode can be found from the dispersion equation (cf. eq. 5.5 in Miles 1958):

$$-\frac{1}{\omega^2} - \frac{c_h^2/c_c^2}{(\omega - Mc_h k)^2} + \frac{1}{k^2 c_c^2} = 0, \quad (2)$$

where c_c and c_h are the velocities of sound in the cold and hot gas, respectively, and k and ω is the wave number and frequency. In solving this equation, we should take into account the adiabatic compression of the hot gas as it arrives at the surface of the cold cloud from infinity, where it flows at our measured Mach number $M_\infty \approx 1$. The velocity of sound as a function of the local Mach number is (e.g., Landau & Lifshitz 1959)

$$\frac{c_h^2}{c_\infty^2} = \frac{T_h}{T_\infty} = \frac{1 + 1/2(\gamma - 1)M_\infty^2}{1 + 1/2(\gamma - 1)M^2}, \quad (3)$$

where c_∞ is the velocity of sound in the inflowing gas at infinity, $c_\infty = (1.37 \pm 0.07)c_c$ for the actual temperatures inside and outside our cloud (§ 2), and $\gamma = 5/3$ is the adiabatic index. For plausible values of M , equation (2) has two complex roots, one of which corresponds to the growing mode. The instability growth time is $\tau = (\text{Im}\omega)^{-1}$. Perturbations of all scales are unstable, but for some scales, the instability may develop slowly compared to the lifetime of the front. The relevant time scale with which τ should be compared is the cluster core passage time, $t_{\text{cross}} = L/M_\infty c_\infty$, where L is the cluster size. The value of $\exp(t_{\text{cross}}/\tau)$ is the perturbation growth factor over the period of time it takes the cool gas cloud to travel the distance L ; if $t_{\text{cross}}/\tau > 1$, the perturbation is effectively unstable.

For the observed gas temperatures and $M_\infty = 1$, the numerical solution of eq. (2) for $M < 1$, the regime relevant for our region of interest, gives the approximate relation $t_{\text{cross}}/\tau = 0.075ML/l$, where $l = 2\pi/k$ is the perturbation wavelength. Combining this with the distribution of the Mach number on the surface of the sphere (eq. 1), we have

$$\frac{t_{\text{cross}}}{\tau} \simeq 0.083 \frac{L}{l} \sin \varphi. \quad (4)$$

For a cluster-scale length of $L = 1$ Mpc, we find that a 10 kpc perturbation becomes effectively unstable already for $\varphi = 7^\circ$. At $\varphi = 30^\circ$, perturbations with $l < 45$ kpc are unstable. However, the front appears undisturbed within at least 30° around the direction of motion. Recall that the observed width of the front is smaller than 5 kpc, and a 45 kpc widening would be easily observable. Therefore, the K-H instability of the cold front must be suppressed.

Long-wavelength K-H perturbations can be stabilized by a gravitational field perpendicular to the interface (e.g., Lamb 1945). However, we find that for the gravitational acceleration estimated from the gas pressure gradient outside the cloud, only $l > 4500M^2$ kpc modes are stable, and therefore gravity is unimportant for the wavelengths of interest.

6. SUPPRESSION OF THE KELVIN-HELMHOLTZ INSTABILITY BY MAGNETIC FIELD

The K-H instability can be suppressed by the surface tension of a magnetic field, if the magnetic field is parallel to the interface and to the direction of the flow. Our considerations can be greatly simplified by the fact that the gas can be treated as incompressible on both sides of the cold front in the region of interest, $\varphi \lesssim 30^\circ$. The outer gas can be considered incompressible because it flows with a relatively low local Mach

number $M \lesssim 0.5$. The cool gas can be considered incompressible because the growing modes of the K-H instability generally have low phase speed. Indeed, the solution of eq. (2) obtained above is very close to the solution in the incompressible limit $c_h, c_c \rightarrow \infty$ for the gas velocities of interest. The interface between the two incompressible magnetized fluids is stable if

$$B_h^2 + B_c^2 > 4\pi \frac{\rho_h \rho_c}{\rho_h + \rho_c} V^2, \quad (5)$$

where B_h and B_c is the magnetic field strength in the hot and cool gas, ρ_h and ρ_c are the gas densities, and V is tangential velocity of the hot gas (e.g., Landau & Lifshitz 1960, § 53). If the magnetic pressure is small compared to the thermal pressure, p (as it turns out to be the case), or is the same fraction of p on both sides of the interface, the stability condition (5) can be rewritten in terms of the thermal pressure and temperature of the gas:

$$\frac{B_h^2}{8\pi} + \frac{B_c^2}{8\pi} > \frac{1}{2} \frac{\gamma M^2}{1 + T_c/T_h} p. \quad (6)$$

The stability of the cold front within $\varphi < 30^\circ$ of the direction of the cloud motion, where $M \leq 0.55$, requires $(B_h^2 + B_c^2)/8\pi > 0.17p$ for the observed ratio of T_c/T_h . If smearing of the surface brightness edge at angles $\varphi \gtrsim 30^\circ$ is interpreted as the development of the K-H instability, this lower limit becomes a measurement of the magnetic pressure.

If magnetic field is too weak to suppress the K-H instability completely, it still increases the instability growth time, which is then

$$(\text{Im}\omega)^{-1} = k^{-1} \left[V^2 \frac{\rho_c \rho_h}{(\rho_c + \rho_h)^2} - \frac{B_h^2 + B_c^2}{4\pi(\rho_c + \rho_h)} \right]^{-1/2}. \quad (7)$$

Thus, even with a weaker magnetic field, the interface can be effectively stable on the time scale of the cluster core passage. However, eq. (7) shows that this quickly becomes unimportant as the magnetic field strength decreases below the stability limit. For example, for B of only 0.7–0.8 of the stability limit, the growth time is 1.1–1.4 of its value for $B = 0$.

The measurement uncertainty in the derived value of the magnetic field strength is mostly due to uncertainty in the angle, φ_{cr} , where the interface becomes unstable, and hence in the local Mach number of the hot gas. For φ_{cr} in the range $30^\circ \pm 10^\circ$ (which appears to be a conservative interval, see Fig. 1), we find from eq. (5) and (1) that the magnetic field strengths are in the interval

$$0.09p < (B_h^2 + B_c^2)/8\pi < 0.23p. \quad (8)$$

Our method directly constrains only the sum of magnetic pressures on the two sides of the interface. The maximum of the magnetic field strengths in the cold and hot gases, $B =$

$\max(B_h, B_c)$, is in the interval $(4\pi p_{\text{mag}})^{1/2} < B < (8\pi p_{\text{mag}})^{1/2}$, where $p_{\text{mag}} = (B_h^2 + B_c^2)/8\pi$ is constrained by (8). Using the value of gas pressure inside the dense cloud derived in Paper I, we find the corresponding uncertainty interval $7\mu\text{G} < B < 16\mu\text{G}$.

7. DISCUSSION

We showed that the sharpness of the front at small angles from the direction of the cloud motion and its smearing at larger angles can be explained by the existence of a layer in which the magnetic field is roughly parallel to the front and has a strength of order $10\mu\text{G}$. As we discussed above, such a layer may form by stretching the magnetic field lines near the front by tangential gas motions. As a result, the magnetic field strength in this layer is probably higher than in the rest of the intra-cluster gas. The magnetic field amplification on the surface of the plasma cloud is discussed, for example, in Jones, Ryu & Tregillis (1996). An important conclusion is that the magnetic pressure is only a small fraction of the thermal pressure: $p_m/p \sim 0.1 - 0.2$ in the magnetic layer and still lower in the rest of the cluster. If the magnetic pressure were of order of the thermal pressure, the front would be stable for Mach numbers up to $M \sim 2(1 + T_c/T_h)^{1/2} \gamma^{-1/2} = 1.9$, i.e. over the entire surface of the cool gas cloud.

Faraday rotation measurements of the magnetic field outside the cluster cooling flows usually give the values of $\sim 1\mu\text{G}$ (Kim et al. 1991). Since Faraday rotation gives the integral of the magnetic field along the line of sight, there is a considerable uncertainty of the absolute field strength due to unknown degree of entanglement. Near the cold front, the field is straightened and amplified, so our measurement provides a likely upper limit on the absolute field strength in the cluster core.

Finally, we note that our arguments would become invalid if the shape of the front were non-stationary, for example, if the cool gas cloud expands into the low-density medium (as opposed to moving as a whole). However, the front velocity relative to the ambient gas exceeds the velocity of sound within the cloud. Since the *in situ* acceleration of a gas cloud to the supersonic velocity is impossible, the cool gas cloud must have arrived from outside the main cluster. In this case, the fact that the shape of the front remains smooth and circular after traveling a large distance, suggests that the front is in fact close to stationary, and therefore our arguments regarding the magnetic field are valid.

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