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DYNAMICS AND MAGNETIZATION IN GALAXY CLUSTER CORES TRACED BY X-RAY COLD FRONTS

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ABSTRACT

Cold fronts — density and temperature plasma discontinuities — are ubiquitous in cool cores of galaxy clusters, where they appear as X-ray brightness edges in the intracluster medium, near-concentric with the cluster center. For several well-observed core cold fronts from the literature, we analyze the thermodynamic profiles above and below the front. While the pressure appears continuous across most of the cold fronts, we find that all of them require significant centripetal acceleration inside (beneath) the front. This is naturally explained by tangential bulk flow just below the cold fronts, nearly sonic in most cases, and tangential shear flow involving a fair fraction of the plasma beneath the front. Such shear should generate near-equipartition magnetic fields on scales $\lesssim 50$ pc from the front, and could magnetize the entire core. Such fields would explain the apparent stability of cool-core cold fronts and the cold front–radio minihalo association reported recently.

Subject headings: galaxies: clusters: general — intergalactic medium — X-rays: galaxies: clusters — hydrodynamics — cooling flows — magnetic fields

1. INTRODUCTION

In the past decade, high resolution X-ray observations have revealed an abundance of density and temperature discontinuities known as cold fronts (CFs). They were found in about half of the clusters observed at low ($z < 0.1$) redshift (*e.g.,* Ghizzardi et al. 2006). For review, see Markevitch & Vikhlinin (2007).

Some CFs are associated with mergers, and thought to separate the intracluster medium (ICM) from the exposed low entropy core of a merging subcluster or galaxy stripped of its envelope. These are relatively strong discontinuities, with temperature contrast $q \sim 2-5$. A pressure discontinuity is sometimes observed across these CFs, usually interpreted as arising from an unresolved precursor caused by motion of the CF through the ICM, thus providing a measure of their relative velocity (Vikhlinin et al. 2001a).

Most CFs, however, are more subtle and not associated with mergers. They have $q \equiv T_o/T_i \sim 1-3$ (Owers et al. 2009), where inside/outside subscripts i/o refer to regions closer to/farther from the cluster center, or equivalently below/above the CF. Such CFs are observed in more than half of the otherwise relaxed, cool core clusters (CCs, Markevitch et al. 2003), in distances ranging from 10 kpc to ~ 400 kpc from the center. They are usually nearly concentric or spiral; multiple CFs are often observed in the same cluster. The plasma beneath the CF is typically denser, colder, lower in entropy and higher in metallicity than the plasma above it. Usually, little or no pressure discontinuity is identified across these CFs, suggesting negligible CF motion.

Such CFs were modeled as associated with large scale "sloshing" oscillations of the ICM driven, for example, by mergers (Markevitch et al. 2001, henceforth M01), possibly involving only a dark matter subhalo (Tittley & Henriksen 2005; Ascasibar & Markevitch 2006), or by weak shocks/acoustic waves displacing cold central plasma (Churazov et al. 2003; Fujita et al. 2004).

In §2 we show that deviations from hydrostatic equilibrium, previously reported in two CC CFs, are common among cool core CFs, and argue in §3 that this directly gauges bulk tangential flows and shear along and beneath these CFs. In §4 we show that such shear can magnetize the core, and produce near-equipartition fields along CFs, thus stabilizing them. We discuss the implications for radio minihalos (MHs) in §5, and summarize in §6. We assume a Hubble constant $H = 70$ km s^{-1} Mpc^{-1}.

2. DEVIATIONS FROM HYDROSTATIC EQUILIBRIUM

The mass density $\rho(r)$ and pressure $P(r)$ radial profiles near CFs in RX J1720+26 and A1795 were found to be inconsistent with hydrostatic equilibrium. Indeed, assuming such equilibrium, $a_r = -\rho^{-1}\partial_r P - GM_g/r^2 = 0$, where a_r is the radial acceleration and G is Newton's constant, would imply an unphysical gravitating mass profile $M_g(r)$ that becomes abruptly larger just outside the CF. In RX J1720, M_g derived from the above assumption jumps by a factor of 5 (at a 2.5σ confidence level), and there is marginal evidence for a pressure discontinuity which translates to radial CF motion with Mach number $\mathcal{M} = 0.4^{+0.7}_{-0.4}$ (Mazzotta et al. 2001). In A1795, M_g jumps by a factor of 2 (2.5σ) and the pressure appears continuous across the CF (Fig. 1, inset; see M01).

To investigate the prevalence of this phenomenon, we calculate the pressure acceleration discontinuity $\Delta a_r = \Delta(-\rho^{-1}\partial_r P) = -(k_B/\mu r)\Delta(\lambda T)$ across various CFs for which deprojected thermodynamic profiles have appeared in the literature. Here we defined $\Delta A \equiv A_i - A_o$ (for any quantity A) and $\lambda \equiv \partial \ln P/\partial \ln r$ (typically $\lambda < 0$), with k_B the Boltzmann constant, $\mu \simeq 0.6 m_p$ the average particle mass (assumed constant), and m_p the proton mass.

Measuring λ by differentiating P on each side of the CF suggests nonzero $\Delta a_r < 0$, but with large uncertainty. Significant results can be derived by making some assumption, such as approximating the pressure profile

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on each side of the CF as a local power law. As shown in Fig. 1, in all cases this yields Δa_r values negative and mostly inconsistent with zero, at a confidence level of up to 3σ. Note that resolution effects alone would introduce an opposite bias towards $\Delta a_r > 0$, as $(-\rho^{-1}\partial_r P)$ typically declines with increasing r.

We conclude that deviations from hydrostatic equilibrium are common in CC CFs, with less pressure support below the CF, $\Delta a_r < 0$, such that if the plasma above the CF is in equilibrium, the plasma below should be falling. Indeed, as T jumps by a factor of $q \simeq 2$ as one crosses outside the CF, hydrostatic equilibrium would require a slower radial decline of pressure outside the CF, $\lambda_i/\lambda_o \simeq q$. However, the pressure profile typically *steepens* outside the CF.

This phenomenon has previously been interpreted as evidence that the core is sloshing, with plasma near the CF *radially* accelerating in some phase of the oscillation cycle. For the apparently stationary CF in A1795, cool plasma would then be sloshing at its maximal radial displacement, where it has zero radial velocity but nonzero radial acceleration (M01).

We note, however, that in this picture, without additional effects, the discontinuity in radial acceleration $\Delta a_r \equiv a_{r,i} - a_{r,o} < 0$ would cause an unphysical gap to open along the CF. A different interpretation of the observations is therefore required. Below we argue that the observations imply a noncontinuous centripetal acceleration of flow along the curved CF.

3. TANGENTIAL SHEAR FLOW BENEATH CFS

Consider an infinitesimal, 2D piece $\mathcal{F}_2$ of the CF plane, and an inertial "CF frame" S' instantaneously comoving with $\mathcal{F}_2$ perpendicular to the CF plane. Let $\mathcal{F}_1$ be an arc in $\mathcal{F}_2$ parallel to the local flow beneath the CF. We may approximate $\mathcal{F}_1$ as a segment of a large circle with radius R. Consider the spherical coordinate system $S' = (r', \theta, \phi)$ with $\mathcal{F}_1$ lying at radius $r' = R$ and colatitude $\theta = \pi/2$. Its origin, the center of the circle, is typically close but not necessarily coincident with the cluster center. See illustration in Fig. 2.

The r' component of the velocity $\mathbf{u}$ measured in S' must vanish at $\mathcal{F}_2$, $u_{r'} = 0$, as $\hat{\mathbf{r}}'$ is perpendicular to the discontinuity. The r' component of the acceleration is continuous across $\mathcal{F}_2$, $\Delta(\partial_t u_{r'}) = 0$. Hence, taking the difference in the r' component of the Euler (momentum) equation between the two sides of $\mathcal{F}_2$ yields

$$\Delta(u^2)/r' = \Delta(\rho^{-1}\partial_{r'} P) \ , \tag{1}$$

where the pressure $P = P_{th} + P_{nt}$ may include thermal and nonthermal components, $u^2 \equiv \mathbf{u}\cdot\mathbf{u} = u_\phi^2 + u_\theta^2$, and we assumed slow changes in CF pattern, $\mathbf{u}\cdot\boldsymbol{\nabla} u_{r'} \ll u^2/r'$. Note that although $\mathbf{u}$ is confined to the CF plane, it does not have to be parallel on the two sides of $\mathcal{F}_2$.

Equation (1) indicates that the observed discontinuity $\Delta(\rho^{-1}\partial_{r'} P_{th}) > 0$ must be balanced by discontinuously larger centripetal acceleration u^2/r' beneath the CF. The discontinuity cannot be plausibly attributed to P_{nt}, because the continuous P_{th}, noncontinuous $\boldsymbol{\nabla} P_{th}$ combination observed would then require predominantly nonthermal pressure at large, sometimes $r > 50$ kpc radii, which is unlikely (*e.g.,* Churazov et al. 2008). Henceforth we neglect P_{nt}.

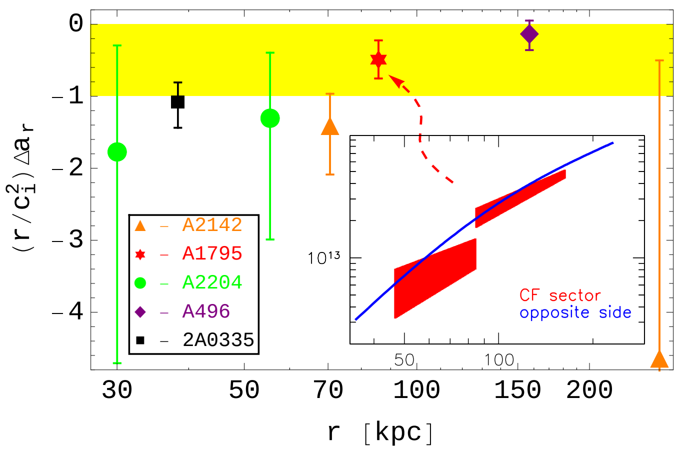

Figure 1. Normalized discontinuity in pressure acceleration $(r/c_i^2)\Delta a_r$, with c the sound velocity, plotted against radius r for CFs in various CCs. Data from Markevitch et al. (2000, for A2142), M01 (for A1795), Sanders et al. (2005, for A2204), Tanaka et al. (2006, for A496), and Sanders et al. (2009, for 2A0335). Error bars are 1σ. The $-1 < (r/c_i^2)\Delta a_r < 0$ (shaded) region is roughly consistent with subsonic shear and flow beneath the CF, $0 < \Delta(u^2) = (u_i+u_o)\Delta u < c_i^2$. The pressure is (consistent with being) continuous in all CFs except A496, where a possible ~ 1.2 pressure jump may be present (1.6σ). A possible trend of $(r/c_i^2)\Delta a_r$ increasing with r will be investigated in future work. Inset: Gravitating mass (in $M_\odot$) assuming hydrostatic equilibrium, as a function of r (in kpc) in two opposite sectors in A1795, one harboring the CF analyzed (adopted from M01).

We conclude that shear flow across CFs is the most natural interpretation of the observations. Thus

$$u_i^2 - u_o^2 = \Delta(u^2) \simeq (k_B/\mu)\Delta(\lambda' T) > 0 \ , \tag{2}$$

where $\lambda' \equiv \partial \ln P/\partial \ln r' \simeq (r'/r)(\hat{\boldsymbol{r}}\cdot\hat{\boldsymbol{r}}')\lambda \approx \lambda$. Hence, CFs are tangential discontinuities, with measurable shear and faster tangential flow beneath the CF, $u_i > u_o$. In particular, $\Delta u \le \Delta u_2 \le u_i$, where $\Delta u_2 \equiv [\Delta(u^2)]^{1/2}$.

In terms of the local sound velocity $c = (\Gamma P/\rho)^{1/2}$, where $\Gamma = 5/3$ is the adiabatic index, Eq. (2) becomes

$$\Gamma\Delta(u^2) = (q^{-1}\lambda_i' - \lambda_o')c_o^2 = (\lambda_i' - \lambda_o' q)c_i^2 \ . \tag{3}$$

Typically the P slopes are $\lambda_i \gtrsim -0.7$, steepening to $\lambda_o \lesssim -1$ above the CF, so subsonic flow in the CF frame ($u_i <$

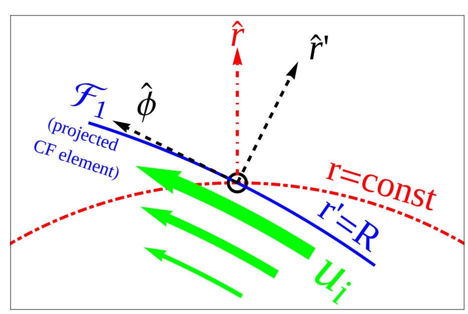

Figure 2. Local geometry of the CF and the inner flow. The radius of curvature R of $\mathcal{F}_1$ (solid curve) at a given position (circle) is typically slightly larger than the distance r (dot-dashed) from the cluster center. The flow (filled arrows, arbitrarily shown as an outflow) must parallel $\mathcal{F}_2$ in a frame S' (dashed axes) comoving with the CF. The observed M_g profile implies that shear flow extends far beneath the CF (filled arrows of different sizes).

c_i) requires $q \lesssim 2.4$. Indeed, $q \lesssim 2.5$ is observed in CC CFs (Owers et al. 2009). Assuming subsonic flow and continuous pressure, Eq. (3) also imposes an upper limit on the velocity above the CF, $\mathcal{M}_o^2 < q^{-1} + \lambda'_o/\Gamma - \lambda'_i/(\Gamma q)$.

As an example, consider the CF in A1795. The M_g discontinuity was previously interpreted as reflecting radial acceleration, $a \sim 2 \times 10^{-8}$ cm s^{-2}. Interpreted as tangential flow, this corresponds to $\Delta u_2 \simeq (ar)^{1/2} \sim 750$ km s^{-1}, uncertain to within a factor of ~ 2. This velocity difference constitutes a considerable fraction of the sound velocity, $\Delta u_2 \simeq 0.67 c_i \simeq 0.55 c_o$. It places a lower limit $\mathcal{M}_i > 0.67$ on the Mach number beneath the CF, and an upper limit $\Delta u < 0.67 c_i$ on the shear across it. Assuming $\mathcal{M}_i < 1$, it also imposes an upper limit $\mathcal{M}_o < 0.61$ on the flow above the CF.

Note that tangential flow inferred from $\Delta a_r \neq 0$ may coexist with perpendicular (radial) motion of the CF through the ICM, inferred from an apparent pressure discontinuity, for example in A3667 (Vikhlinin et al. 2001a) and possibly in RX J1720+26 (Mazzotta et al. 2001).

The $M_g(r)$ profile near a CF can be compared to other, equidistant regions in the core, preferably on the opposite side of the cluster, that do not harbor discontinuities. In both cases examined, A1795 (Fig. 1, inset) and RX J1720+26, this yields agreement in M_g above the CF, but indicates missing inertia (M_g is too small) in most of the volume beneath it. In the tangential flow picture, the missing inertia region beneath the CF corresponds to extended bulk flow. Consider again the CF lying $r_0 \simeq 85$ kpc south of the center of A1795. Here, inertia appears to be missing in a considerable, $0.7 \lesssim r/r_0 < 1$ region, involving $\sim 1/2$ of the baryons in that sector. There is no evidence for inertia discrepancy below $\sim 0.6 r_0$. Hence, plasma within the discrepant radii range cannot be uniformly flowing; shear must be present.

4. MAGNETIC SHEAR AMPLIFICATION

An independent argument implying shear across CFs stems from their remarkable sharpness and stability. Stationary CFs are stable against Rayleigh-Taylor instabilities, as the inside plasma has lower entropy. However, particle diffusion, heat conduction, and instabilities such as Kelvin-Helmholtz (KHI) and Richtmyer-Meshkov, could potentially broaden and deteriorate the CF on short, subdynamical time scales. In contrast, observations indicate that CFs are not only stable over cosmological time scales, but in fact the transition in thermodynamical properties subtends a small fraction of the Coulomb mean free path of protons (Vikhlinin et al. 2001a; Markevitch & Vikhlinin 2007).

This suggests that transport across CFs is magnetically suppressed. Such suppression is expected in CFs that move through the ICM, due to draping of magnetic fields and possibly the formation of a magnetic barrier (plasma depletion layer), as found in observations of planetary magnetospheres and in simulations (Lyutikov 2006, and references therein). However, the processes that suppress transport in the more common, stationary type of CFs, were thus far unknown. Here we argue that shear magnetic amplification near CFs naturally sustains the strong magnetic fields parallel to the CF needed to suppress radial transport.

Consider first the limit where CFs are infinitely sharp tangential discontinuities. The magnetic field perpendicular to such a CF must vanish, and there is no shear magnetic amplification. However, in this limit the stability against KHI inferred from observations requires a strong magnetic field $\mathbf{B}$, as shown by Vikhlinin et al. (2001b) for the merger CF in A3667. Namely, the shear velocity difference must be smaller than an effective Alfvén velocity (Landau & Lifshitz 1960, §53),

$$\left(\frac{\Delta u}{2}\right)^2 < \frac{\bar{B}^2}{4\pi\bar{\rho}} \simeq \frac{3(1+q)}{5\bar{\beta}_i} c_i^2 \ , \tag{4}$$

and in addition

$$(\mathbf{B}_i \times \mathbf{B}_o)^2 \geq 2\pi\bar{\rho}\left[(\mathbf{B}_i \times \Delta\mathbf{u})^2 + (\mathbf{B}_o \times \Delta\mathbf{u})^2\right] \ , \tag{5}$$

where $\bar{B}^2 \equiv (B_i^2 + B_o^2)/2$, $\bar{\rho} = 2\rho_i\rho_o/(\rho_i + \rho_o)$, and $\bar{\beta} \equiv P_{th}/P_{\bar{B}} = 8\pi n k_B T/\bar{B}^2$, with n the number density.

Equation (4) imposes a lower limit on $\bar{B}$,

$$\bar{B} > B_{min} \equiv \sqrt{\frac{2\pi\rho_i}{1+q}}|\Delta u| = \sqrt{\frac{5}{12(1+q)}}\frac{|\Delta u|}{c_i} B_{eq,i}$$
$$\simeq 17\mathcal{M}_i \sqrt{\frac{3 n_i k_B T_i/(1+q)}{50 \text{ eV cm}^{-3}}} \ \mu\text{G} \ . \tag{6}$$

The large shear velocities derived above thus imply large $\bar{B}$, up to $\sim 40\%$ of its equipartition value B_{eq} for which $\beta = 1$. An asymmetry $B_i/B_o \neq 1$ would require $\mathbf{B}$ well aligned with $\Delta\mathbf{u}$. In the case $B_i = B_o = B$, $\alpha_i \neq \alpha_o$,

$$B > \sqrt{\frac{2(\sin^2\alpha_i + \sin^2\alpha_o)}{\sin^2(\alpha_i - \alpha_o)}} B_{min} \ , \tag{7}$$

with α the angle between $\mathbf{B}$ and $\Delta\mathbf{u}$, so stronger fields are needed if misaligned with the shear.

A magnetic, plasma depleted barrier may form. As long as its temperature does not greatly exceed T_o, it remains strongly magnetized. Note that the corresponding density drop could possibly be observed more easily here than in merger-type CFs, as there is no confusion with a stagnation region. As shown below, equipartition fields are expected only very close to the CF, so P_{nt} can still be neglected at $\gtrsim$ kpc distances, as assumed in §3.

How did strong magnetic fields form along stationary CFs, and how are they sustained over cosmological time scales? Perpendicular transport suppression could preserve such fields practically indefinitely in the absence of large perturbations (*e.g.,* mergers) and disruptive kinetic plasma effects. Hence, they could be remnants of an early stage where the CF was formed. But if such initial fields are absent or decay, shear driven magnetic amplification can naturally generate or replenish B_ϕ, by stretching $B_{r'} \neq 0$ magnetic structures advected by the flow via line freezing, $d(\mathbf{B}/\rho)/dt \simeq [(\mathbf{B}/\rho)\cdot\nabla]\mathbf{u}$.

Consider a weakly magnetized, $B \ll B_{eq}$ stage where the kinematic viscosity ν is a fraction f_ν of its Spitzer value. The velocity discontinuity across such a CF is gradually smoothed out, forming a transition layer of thickness $\delta \sim (\nu t)^{1/2} \simeq 7 f_\nu^{1/2} T_4^{5/4} n_{-2}^{-1/2} (t/\text{Gyr})^{1/2}$ kpc beneath the CF at time t, where $T_4 \equiv (T_i/4 \text{ keV})$ and $n_{-2} \equiv (n_i/10^{-2} \text{ cm}^{-3})$. This enables rapid shear magnetic amplification, on an e-fold time scale $\tau \sim \delta/u$.

Equating the viscous and amplification times suggests that a magnetization layer of thickness

$$\delta \sim N\nu/u \simeq 50 N f_\nu \mathcal{M}_i^{-1} T_4^2 n_{-2}^{-1} \text{ pc} \quad (8)$$

develops over a very short time scale

$$t \sim N^2\nu/u^2 \simeq 4\times10^4 N^2 f_\nu \mathcal{M}_i^{-2} T_4^{3/2} n_{-2}^{-1} \text{ yr} , \quad (9)$$

with N the growth factor. Typically $N f_\nu < 1$; $N \sim 1$ may suffice in the case of a weakening magnetic barrier.

The high B estimates above hold only in the vicinity of CFs, where fast shear is measured. As mentioned in §3, evidence suggests that the associated shear involves a fair fraction of the plasma beneath the CF. Shear amplification may thus effectively magnetize the entire core, at least beneath the outermost CF. For a simple model where the shear is constant in a layer of thickness Δ beneath the CF, the energy of the frozen magnetic field is amplified in proportion to $(B_\phi/B_{r'})^2$, where

$$\frac{B_\phi}{B_{r'}} \sim t\partial_{r'}u \sim 10\mathcal{M}_i T_4^{1/2}\left(\frac{\Delta}{10\text{ kpc}}\right)^{-1}\left(\frac{t}{10^8\text{ yr}}\right) \quad (10)$$

Saturation of this process depends on the flow details. For example, in a spiral flow there is a characteristic cutoff time when magnetic structures leave the shear region.

We have seen that CFs are strongly magnetized, and the associated shear flow can magnetize much of the plasma beneath them. Magnetic processes should therefore be enhanced below, and in particular near CFs. This naturally explains the recently discovered coincidence between CFs and MH edges (Mazzotta & Giacintucci 2008).

5. RADIO MINIHALOS

MHs are diffuse radio emission found in CCs. Their size is comparable to the cooling region (Gitti et al. 2002), much smaller than their giant halo relatives. MHs are believed to be synchrotron emission from relativistic electrons gyrating in $\gtrsim$ μG magnetic fields (Murgia et al. 2009, and references therein). Magnetization by shear flow beneath the CFs could sustain such magnetic fields and, as the shear apparently diminishes above the CF, naturally explains why the radio emission sometimes abruptly truncates at CFs. Conversely, the observed radio cutoff above CFs suggests lower magnetization there, supporting our model for shear flow below the CF but little flow above it (see upper limits on M_o).

We predict enhanced radio emission where CFs are observed (edge on). More generally, we anticipate detailed morphological correlations between radio maps and spatial X-ray gradients that trace projected CFs. Near CF edges, the emitted radio signal should be strongly polarized perpendicular to the CF. CFs are usually nearly concentric, so **B** should be mostly tangential and the polarization radial. Note that this magnetic configuration differs from the predictions of magnetic compression models, where **B** is typically isotropic (*e.g.,* Gitti et al. 2002) or radial (Soker & Sarazin 1990), but is similar to the saturation of heat flux driven buoyancy instabilities in the core (Quataert 2008). Non radial polarization may persist where plasma flows perpendicular to the line of sight, along a face-on CF.

In our model, radio polarization would directly gauge the bulk flow orientation. However, this signal is obscured by strong depolarization, as the emitting electrons are well mixed with the ionized plasma. Indeed, little or no polarization is typically found in MHs, with upper limits as low as $< 0.2\%$ (in PKS 0745-191, Baum & O'Dea 1991). Polarization might be detected in the lower density outskirts of MHs, in particular near the outermost CFs in hot clusters, if the flow (and hence the magnetic field) is predominately aligned in the plane of the sky. Interestingly, nearly radial, $10\% - 20\%$ polarization was detected along the edge of the MH in A2390, one of the hottest clusters observed (Bacchi et al. 2003, we refer to the spherical, $r \sim 150$ kpc component around the cD galaxy in this irregular MH).

6. DISCUSSION

We interpret deviations from hydrostatic equilibrium previously observed near CFs as evidence for centripetal acceleration. This reveals tangential shear flow, nearly sonic at the CFs and extending well beneath them. Such behavior is shown to be common among of CC CFs, as illustrated in Fig. 1. The measured discontinuity $\Delta(u^2)$, given by Eqs. (2-3), constrains the shear and inside flow, $\Delta u \le \Delta u_2 \le u_i$, and imposes an upper limit on $\mathcal{M}_o$. The apparent CF stability against KHI suggests near-equipartition magnetic fields along the CF (Eqs. 6-7); this could manifest in a shear-amplified, $\lesssim 50$ pc magnetic layer. Shear magnetic amplification could rapidly magnetize the entire core up to the CFs, and explain some of the observed properties of radio MHs.

In our model, CC CFs are part of extended tangential discontinuities seen in projection. They directly trace both the orientation and approximate magnitude of bulk flows in the ICM. We predict a correlation between the presence of CFs and MHs, detailed morphological correlations between radio emission and X-ray gradients, and predominately radial radio polarization perpendicular to the flow, stronger at MH outskirts.

Such fast, extended flows would modify the energy budget of the core and could alter its structure, for example by distributing heat and relaxing the cooling problem. Churazov et al. (2003) pointed out that absence of resonant features in the X-ray spectrum in Perseus indicates motions with at least $\mathcal{M} = 1/2$ in the core. Although interpreted as turbulent motion, this may reflect the bulk motions discussed here. The presence of such flows could be tested, for example using high resolution spectroscopy and future X-ray polarization measurements (*e.g.,* Sazonov et al. 2002).

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