AGN Feedback in Clusters: the Feedback Cycle

Paul Nulsen

Harvard-Smithsonian Center for Astrophysics

McNamara & Nulsen (2012),
New Journal of Physics, in press
arXiv:1204.0006

Feedback is Needed

General energy equation: $\rho T \frac{dS}{dt} = \mathscr{H} - \mathscr{R}$ can be written: $\frac{d}{dt}\ln K = \frac{1}{t_\mathrm{h}} - \frac{1}{t_\mathrm{c}}$

Entropy index: $K = kT / n_\mathrm{e}^{\gamma-1}$ Cooling time: $t_\mathrm{c} = \frac{p}{(\gamma-1)\mathscr{R}}$

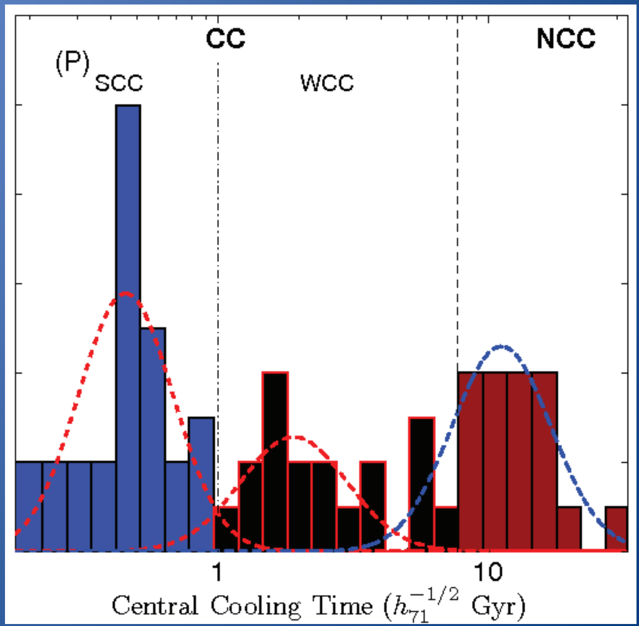
Heating time: $t_\mathrm{h} = \frac{p}{(\gamma-1)\mathscr{H}}$

Cooling wins if $t_c < t_h$ => a lot of gas should cool (cf. Peterson & Fabian 2006)

Heating wins if $t_c > t_h$ => generally t_h -> t, so that $t_c = t_h \mathscr{H} / \mathscr{R} >> t$

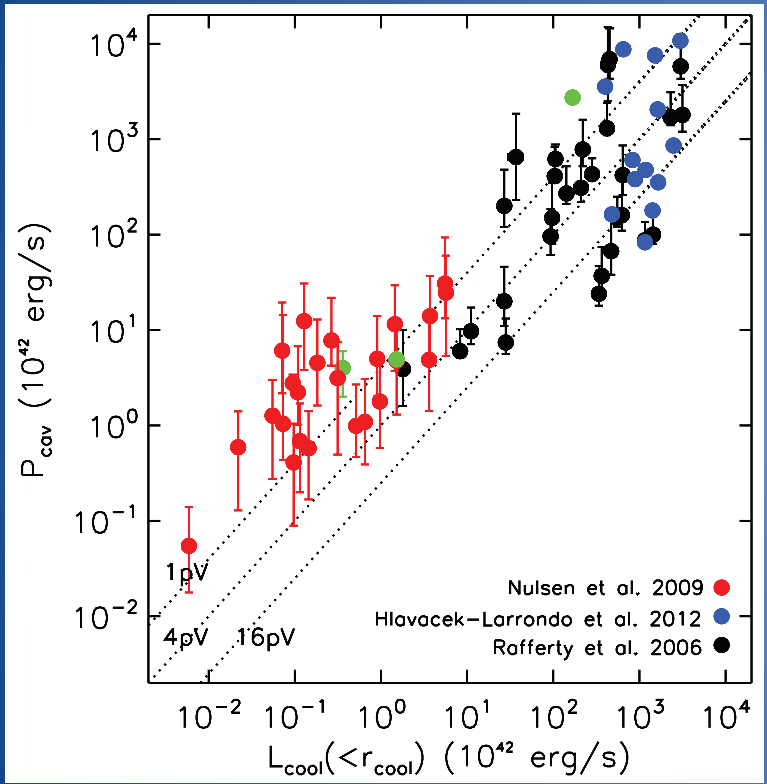
Hudson et al (2010): 44% of HIFLUGCS sample clusters have central cooling times < 1 Gyr

High incidence of short central cooling times, with very little cooling is difficult to explain without feedback



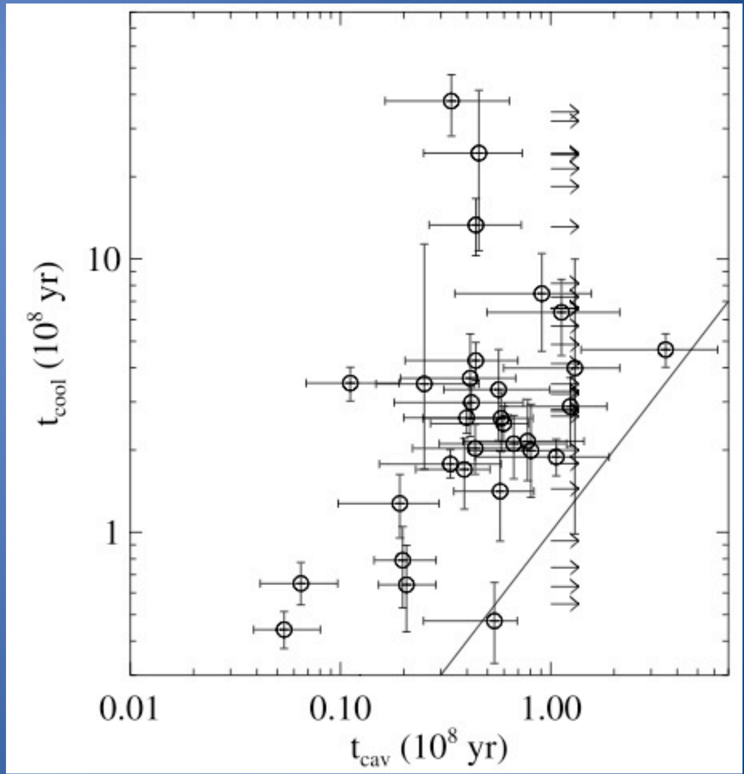
Feedback is Consistent with Cavities

Cavity powers scale with cooling power



Fabian 2012

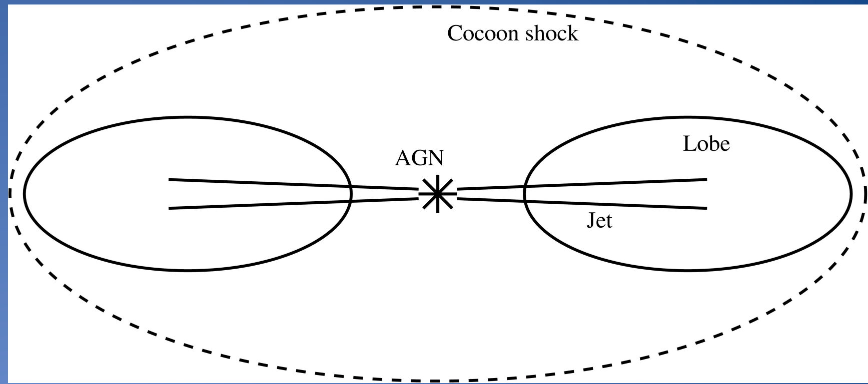
Cavities are young enough to prevent catastrophic cooling (Rafferty 2008)



Radio AGN Energy Deposition

Power flows from the AGN through opposed jets into surrounding gas

Jets inflate radio lobes that push aside the gas, possibly driving shocks and/or sound waves



Jet energy is divided between the lobes (internal energy) and gas (thermal, kinetic, gravitational potential)

Internal energies of cavities found to be comparable to the p dV work they do on the gas measured from shocks (e.g. McNamara et al. 2005, Forman et al 2007).

Cosmic rays can leak from lobes and deposit energy in the ICM (Boehringer & Morfill 1988, Sijacki et al 2008, Mathews & Guo 2010)

Enthalpy lost by buoyant lobes is dissipated in the gas (McNamara & Nulsen 2007)

Ultimately, lobe plasma mixes with the ICM

Jet Anisotropy

Is the anisotropy of jets a problem?

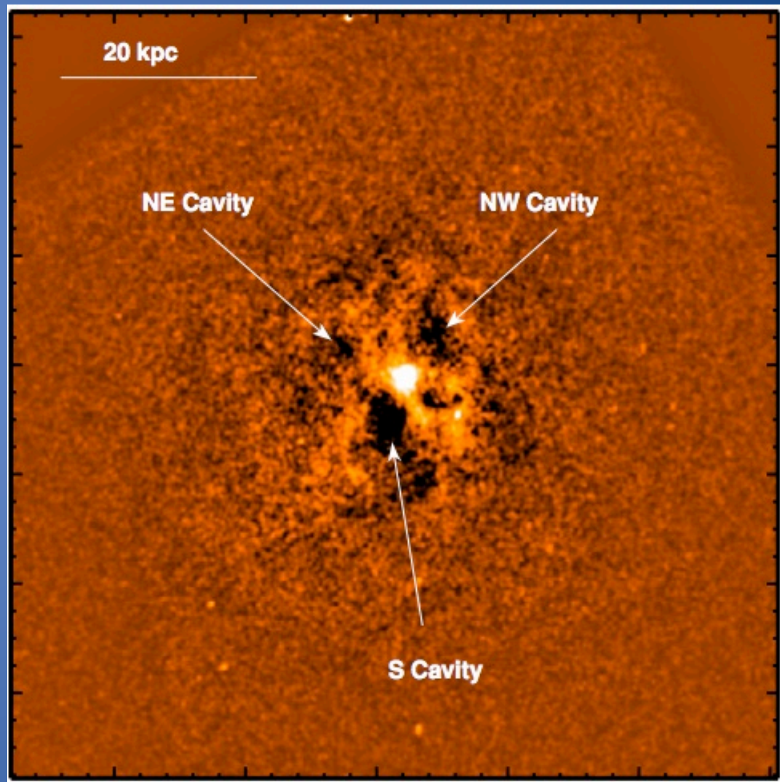
Many systems have multiple cavities (eg M87, Forman et al 2007; Perseus, Fabian et al 2011) and they are not generally colinear

Some systems show cavities in many directions (NGC 5044, David et al 2009; 2A0335+096, Sanders et al 2009)

This may be due to a precessing jet (Dunn et al 2006; King & Pringle 2007; Gaspari et al 2012)

or cluster "weather" (gas flows driven by cluster assembly, Heinz et al 2006; Morsony et al. 2010)

Even without such effects, the lowest entropy gas left after an outburst falls inward, placing it close to the AGN in a subsequent outburst



NGC 5044 (David et al 2009)

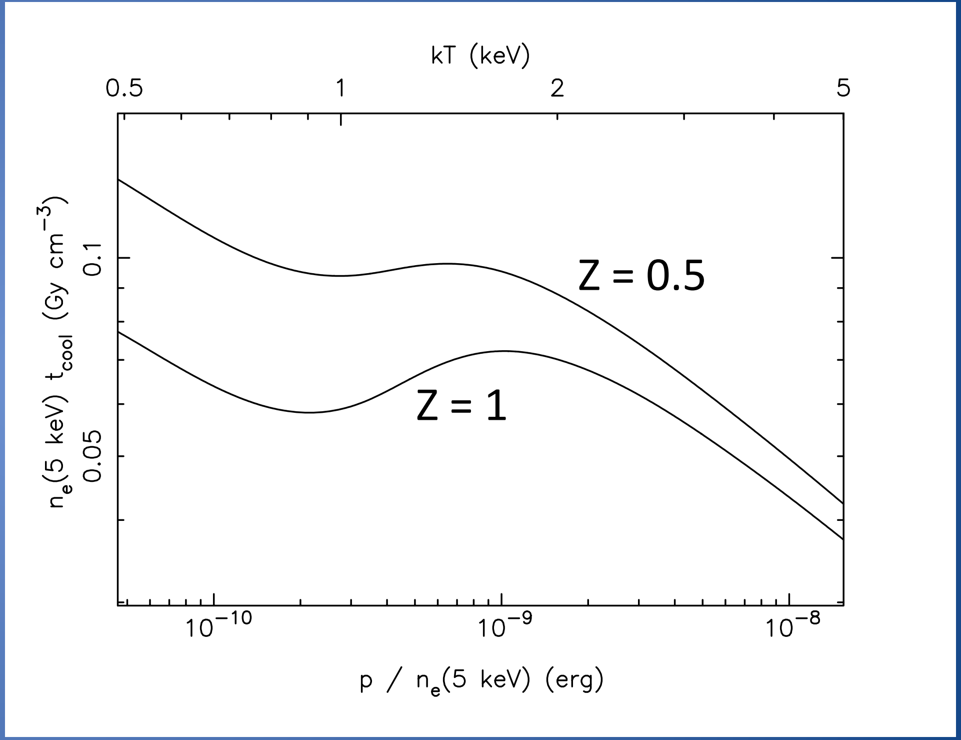
Adiabatic Uplift is Insufficient

Cooling time: $$t_c = \frac{p}{(\gamma - 1) n_e n_H \Lambda(T)}$$

Under pure adiabatic (isentropic) change, $T \sim p^{(\gamma-1)/\gamma}$ and $n_e \sim p^{1/\gamma}$, giving pressure dependence of t_c:

Adiabatic uplift alone is an ineffective way to prevent cooling

Heat lost by cooling must generally be replaced by heat input
– i.e. an entropy increase



Outburst History

Timing *and* power of AGN outbursts matter – i.e. the power spectrum of outbursts

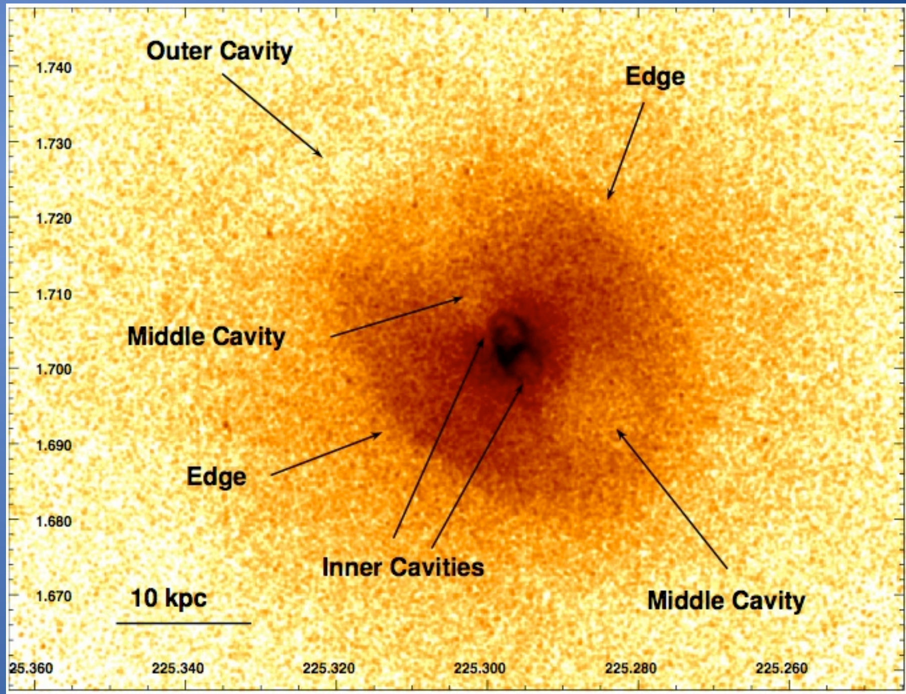
Depositing energy E_{tot} into volume V increases the pressure by $(\gamma - 1) E_{tot} / V$ => large fractional pressure increase unless thermal energy in V exceeds E_{tot}, i.e.

$$\int_V \frac{p}{\gamma - 1} dV > E_{tot}$$

A large fractional pressure increase would drive supersonic inflation, so the smallest region affected by an outburst contains thermal energy ≈ E_{tot}

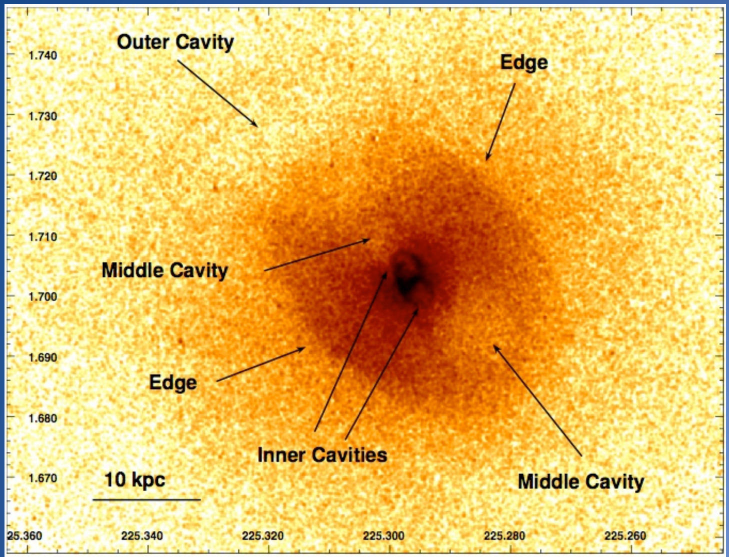
In the presence of "weather," Morsony et al (2010) find that the radius of influence, $R \sim P_{jet}^{1/3}$

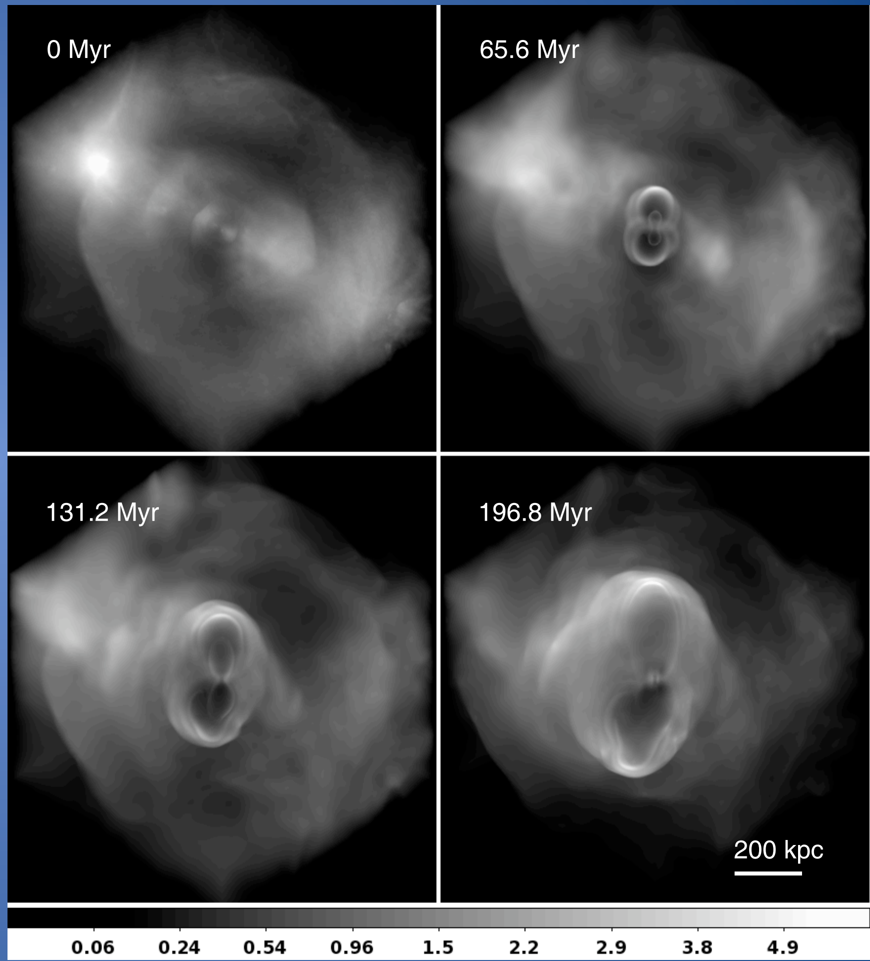
Many systems, including NGC 5813, show signatures of multiple outbursts (varying jet power)



NGC 5813 (Randall et al 2011)

Outburst History and Environment





Large scale symmetry in MS0735.6+7421 (McNamara et al 2005) and NGC 5813 (Randall et al 2011) has survived multiple outburst cycles

Right: Intermittent jet (50% duty cycle) in a cluster with "weather" simulated by Mendygral et al. (2012)

Weak Shock Heating

Weak shocks are insignificant on large scales in clusters (David et al 2001)

Effects of weak shocks are largely transient, apart from a small entropy increase, ΔS [cubic in shock strength, $\delta p/p = 2\gamma (M^2 - 1)/(Y + 1)$]

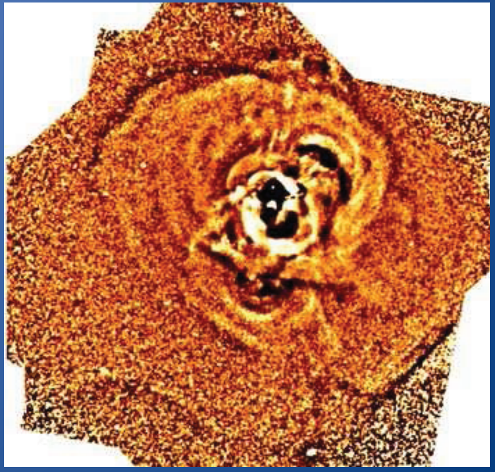
Equivalent heat input, $\Delta Q = T\,\Delta S = E\,\Delta\ln K$, where $K = kT / n_e^{(\gamma - 1)}$ is the entropy index

Near the centre of M87 and in NGC 5813, weak shocks each produce $\Delta Q/E = \Delta\ln K$ of 1 to 10 percent and the shocks repeat on a timescale << cooling time

The average rate of shock heating is enough to replace the power radiated near the AGN in M87 (Nulsen et al. 2007) and NGC 5813 (Randall et al. 2011)

The same mechanism can plausibly work in other systems

The dominant heating mechanism close to the AGN controls short term feedback



Perseus ripples (Fabian et al 2006)

Transport

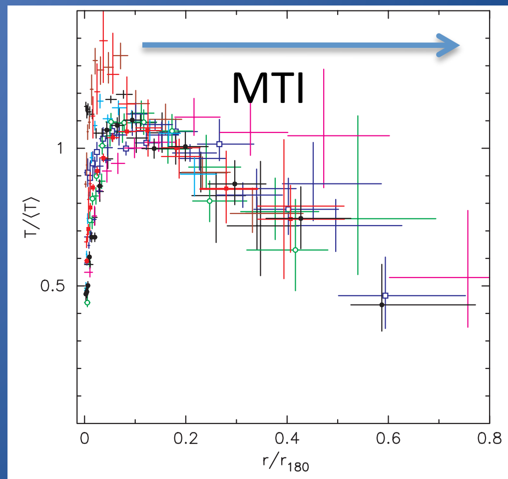
The ratio of the Larmor radius to mean free path for electrons (n_e in cm^{-3}, kT in keV) $\approx 1.3\times10^{-10}\, n_e\, (kT)^{-3/2}\, B_{\mu G}^{-1}$ and for protons it is $\approx 4\times10^{-9}\, n_e\, (kT)^{-3/2}\, B_{\mu G}^{-1}$

=> particles are tied very tightly to magnetic field lines and transport is extremely anisotropic – theory is poorly understood

If the field is chaotic, the net effect may be simply a modest reduction (≈3) in conductive heat flux (Narayan & Medvedev 2001)

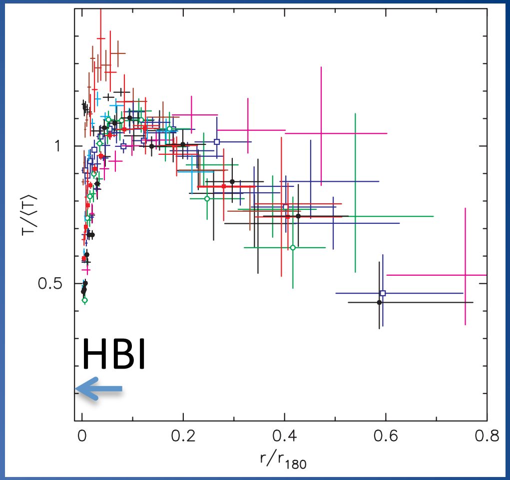
If conduction is highly anisotropic, gas with negative radial temperature gradient is prone to magnetothermal instability (MTI, Balbus 2000; Parrish & Stone 2005)

Fully developed MTI orients field preferentially to be radial, *promoting* heat loss from a cluster centre



Vikhlinin et al (2005)

Transport



Gas with a positive radial temperature gradient is prone to heat flux driven buoyancy instability (HBI, Quataert 2008)

Fully developed HBI drives turbulence that orients field preferentially perpendicular to r, suppressing conduction (Bogdanovic et al 2009; Parrish et al 2009)

The power available to drive HBI turbulence is limited by the conductive heat flux and it is readily overwhelmed by other sources of turbulence

Turbulence can be driven many ways, including AGN activity, minor mergers and moving subhalos

Ruszkowski & Oh (2011) argue that heat diffusion due to turbulence driven by moving subhalos dominates over conduction in cluster cores

Metals shed by evolving stars in the central galaxy are spread by turbulent diffusion (Rebusco et al 2005)

Plasma Effects on Conduction

Simple models for anisotropic heat transport assume heat flows only parallel to the field, with the field free value:

$$\mathbf{h} = \mathbf{b}\kappa\mathbf{b} \bullet \nabla T, \quad \text{where } \mathbf{b} = \mathbf{B} / |\mathbf{B}|$$

At the least, if B varies along field lines, magnetic mirror effect modifies this

Schekochihin et al (2010) argue that “gyrothermal instability” may also limit the parallel heat flux

Plasma Effects on Viscosity

Dynamically insignificant magnetic field means that fluid motions easily change B

Varying B in a collisionless plasma makes the particle velocity distribution anisotropic, since the magnetic moment, ½ m v_{perp}^2 / B, is conserved

Collisions relax the velocity distribution back to isotropy on a timescale, for protons, of $\tau_{pp} \approx 700\ (kT)^{3/2}\ n_e^{-1}$ yr

Viscous stress tensor is the anisotropic part of the total stress tensor, so residual anisotropy represents a viscous stress (Kunz et al 2012)

Effect is local, requiring only that the Larmor radius << mean free path
and the field is not so chaotic that it alters the relaxation time

– insensitive to poorly known structure of the magnetic field

Viscous Sound Dissipation in a Magnetized ICM

Anisotropy of proton pressure can be measured by $\Delta = p_{perp,p} - p_p$, with

$$\frac{d\Delta}{dt} = -\frac{\Delta}{\tau_{\mathrm{pp}}} + p_{\mathrm{p}}(\mathbf{bb} : \nabla \mathbf{v} - \tfrac{1}{3}\nabla \bullet \mathbf{v})$$

and the stress tensor is

$$\mathbf{T} = \Delta(3\mathbf{bb} - \mathbf{1})$$

For motion parallel to the field, must match field free viscous stress => field free kinematic viscosity, $\nu = \tau_{\mathrm{pp}} p_{\mathrm{p}} / \rho$

Damping rate for sound with wavevector k is then $\frac{1}{6}\nu k^2 (1 - 3k_z^2/k^2)^2$ where k_z is the component of k parallel to the field

Averages to 1/5th of the field free rate for isotropic random field

Conclusions

•AGN feedback is needed and supported by the data for cool core clusters

•The power spectrum of outbursts affects where and how energy is deposited

•As does cluster environment, including “weather”

•Heating by repeated weak shocks may dominate close to the AGN

•Plasma effects and magnetic field structure mean that thermal conduction remains poorly understood

•Viscosity is also affected, but is much easier to treat

•Viscous damping of sound is suppressed by a factor of ≈ 5 from its field free value