Cold Fronts and Shock Waves in Merging Clusters

\[ \Delta \Phi \approx 9 \sigma_r^2 \approx 5 c_s^2 \]

\[ M = \frac{v}{c_s} \sim 3 \]

\[ E_{\text{kin}} \sim 10^{63} \text{ erg} \gtrsim E_{\text{th}} \]

• ICM physics exposed
1E0657–56
Markevitch et al. 02, 03
1E0657–56
Markevitch et al. 02, 03

7 keV
19 keV
8 keV

1 Mpc
1E0657–56
Markevitch et al. 02, 03

\[ M = 3.2 \]
(from \( \rho_{\text{in}}/\rho_{\text{out}} = 3.1 \))

1 Mpc
$M = 3.2$

(from $\rho_{in}/\rho_{out} = 3.1$)

$\frac{T_{in}}{T_{out}} = 4.1$ — expected

$\frac{T_{in}}{T_{out}} = 2.5 \pm 0.7$ — observed
$M = 3.2$ (from $\rho_{\text{in}}/\rho_{\text{out}} = 3.1$)

$\frac{T_{\text{in}}}{T_{\text{out}}} = 4.1$ — expected

$\frac{T_{\text{in}}}{T_{\text{out}}} = 2.5 \pm 0.7$ — observed

- electron-ion non-equilibrium?
- non-thermal processes?
- ...

1E0657–56
Markevitch et al. 02, 03
1E0657–56: limits on self-interacting dark matter
Markevitch et al. 03
Clowe et al. 03
1E0657–56: limits on self-interacting dark matter

Mass from weak lensing (Clowe et al. 03)
1E0657–56: limits on self-interacting dark matter
Markevitch et al. 03
Clowe et al. 03
1E0657–56: limits on self-interacting dark matter

Markevitch et al. 03

Clowe et al. 03

\[ \frac{\sigma}{m} < 1 \text{ cm}^2 \text{ g}^{-1} \]
8 keV

4 keV

Cold front, not shock
\[ \frac{p_{\text{in}}}{p_{\text{out}}} = 2.0 \Rightarrow \text{front is moving} \]
\[ \frac{p_{\text{in}}}{p_{\text{out}}} = 2.0 \Rightarrow \text{front is moving} \]

\[ M = 1 \pm 0.2 \]
A3667

front width < 5 kpc
mean free path 20 kpc
A754 — heat conduction in the bulk of the cluster gas

\[ t_{\text{cond}} \sim \frac{kn_e l^2}{\chi_{sp}} \approx 1.2 \times 10^7 \text{ yr} \]

\[ t_{\text{age}} \sim \frac{L}{c_s} \sim 5 \times 10^8 \text{ yr} \]

Conduction suppressed by factor \( \frac{t_{\text{age}}}{t_{\text{cond}}} > 10 \, h_{65}^{1/2} \)

Markevitch et al. 03
A3667

tangential flow near front
\((M = 0.55 \text{ at } 30^\circ)\)

\(\Downarrow\)

KH-instability

\(\Downarrow\)

Turbulent layer
\((10 - 50 \text{ kpc thick})\)
tangential flow near front
\( (M = 0.55 \text{ at } 30^\circ) \)

↓

KH-instability

↓

Turbulent layer
\( (10 - 50 \text{ kpc thick}) \)

not observed

↓

KH-instability suppressed by magnetic tension
A3667

tangential flow near front
($M = 0.55$ at $30^\circ$)
A3667

tangential flow near front
($M = 0.55$ at $30^\circ$)
A3667

tangential flow near front
\( (M = 0.55 \text{ at } 30^\circ) \)

\[ v > v_{cr} \]

\[ P_{mag} \approx 0.1P_{th}, \quad B \approx 10 \mu G \]
$P_{\text{out}} = P_{\text{in}}$

limits on turbulence

A3667

500 kpc
A3667

limits on turbulence

$P_{\text{out}} = P_{\text{in}}$
magnetic tension important if

\[ P_{\text{turb}} < 3P_{\text{mag}} \approx 0.3P_{\text{th}} \text{ or } v_{\text{turb}} \leq 350 \text{ km/s} \]
turbulence ON

$v_{\text{turb}} > 350 \text{ km/s}, \ l_{\text{turb}} \sim 20 \text{ kpc}$
turbulence OFF

\( \nu_{\text{turb}} < 350 \text{ km/s} \) or \( l_{\text{turb}} < 5 \text{ kpc} \)
diffusion, turbulence OFF
diffusion, turbulence ON
\[ \lambda = 25 \text{ kpc} \]
A2142

A3667

Hydra A

Radio from G. Taylor

2A 0335+096

A496

NGC 507 group
CONCLUSIONS

• Shocks (1E 0657–56)
  – Merger dynamics
  – Plasma microphysics (electron-ion non-equilibrium etc.)
  – Constraints on the dark matter properties

• Heat conduction in the *bulk* of the cluster gas (A754): $\kappa < 0.1 \kappa_{Sp}$

• Cold fronts (A3667)
  – Hydrodynamics
  – Suppressed transport processes (diffusion, heat conduction)
  – Magnetic fields
  – Gas sloshing in the centers of relaxed clusters, relation to radio bubbles (Hydra-A)
  – Limits on turbulence