The cooling flow problem and the tsunami model

Yutaka Fujita (Nat. Astron. Obs., Japan)

Fujita et al. (2005)


The authors extend their deepest condolences to the families and friends of the victims of the Indian Ocean tsunami on 2004 December 26.
Clusters of galaxies
- Mass $\sim 10^{13-15} M_\odot$
- Number of galaxies $\sim 100-1000$
- Size $\sim $ Mpc

The most massive gravitationally bounded objects
The diffuse X-ray emission comes from Intracluster medium (ICM). Most baryon in a cluster is in the form of ICM. ICM is mainly thermal hot gas (~2-10 keV).
Intracluster medium (ICM)

**Mass**
- $4 - 10 \times$ total galaxy mass of a cluster
- $1/4 - 1/10 \times$ gravitational mass of a cluster

**Temperature (2-10 keV)**
- Depth of the potential well

**X-ray emission mechanism**
- Bremsstrahlung
The Cooling Flow Problem

Cooling time

\[ t_{\text{cool}} = 8.5 \times 10^{10} \text{ yr} \left( \frac{n}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \left( \frac{T}{10^8 \text{ K}} \right)^{1/2} \]

- Larger than the age of the universe
- Generally, the ICM does not cool

The cluster core \((r \leq 100 \text{ kpc})\) is the exception

- High density \((n \sim 0.1 \text{ cm}^{-1})\), small cooling time \((\sim 10^{8-9} \text{ yr})\)
- Cooling should be effective
Strong X-ray Emission from Cluster Cores

- X-ray luminosity of a core
  - \( \sim 10^{42-45} \) ergs s\(^{-1}\)
  - The ICM loses its thermal energy in \( \sim 10^{8-9} \) yr

3D representation of the X-ray surface brightness of A478 (White et al. 1994)
Because of cooling, gas pressure in the core decreases

- Gas pressure in the core cannot sustain pressure from the outer region
- Cooling flows were thought to be established
Galaxy Formation?

- Expected mass deposition (inflow) rate is huge

\[ L_X \sim \frac{k_B T}{\mu m_p} \dot{M} \]

- X-ray luminosity \( L_X \) and temperature \( T \) can be observed
  - \( \dot{M} \sim 100 \, M_\odot \, \text{yr}^{-1} \)
  - \( \sim 10^{12} \, M_\odot \) for \( 10^{10} \, \text{yr} \)

- Comparable to galaxy mass

Some people thought that cooling flows are laboratories of galaxy formation

- In fact, cD galaxies are located at cluster centers
Evidence of Cooling Flows?

- Temperature decrease toward the cluster center
- Metal emission from cooling gas
- Absorbing material

Fabian et al. (1994)
The Most Serious Problem of the Cooling Flow Model

- Where has the cooling gas gone?
  - $\dot{M} \sim 100 \, M_\odot \, \text{yr}^{-1}$
  - $\sim 10^{12} \, M_\odot$ for $10^{10} \, \text{yr}$

- Star Formation?
  - Star formation rate at cluster centers is $\sim 10 \, M_\odot \, \text{yr}^{-1}$

- Cold Gas?
  - The mass of HI or H$_2$ gas at cluster centers is $\approx 10^{10} \, M_\odot$
I must comment on ASCA results...

- During 80s and 90s, the cooling flow model was supported by most researchers
- However, the Japanese ASCA team indicated that the model was not correct even at that time
  - Emission from cooling gas is not strong

Review by Makishima et al. (2001)
Chandra and XMM-Newton Results

- **Chandra**
  - High angular resolution

- **XMM-Newton**
  - Large collective area

Cooling Flow problem has been widely recognized
### Performance

表1 Newtonとライバル衛星、Chandra, Astro-E2の性能比較。

<table>
<thead>
<tr>
<th></th>
<th>Newton (ヨーロッパ)</th>
<th>Chandra (アメリカ)</th>
<th>Astro-E2 (日本-アメリカ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>打ち上げ (年)</td>
<td>1999</td>
<td>1999</td>
<td>2005</td>
</tr>
<tr>
<td>衛星の重量 (t)</td>
<td>4</td>
<td>4.8</td>
<td>1.7</td>
</tr>
<tr>
<td>全長 (m)</td>
<td>10</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>軌道 近地点 (km)</td>
<td>7,000</td>
<td>16,000</td>
<td>約7,000 (円軌道)</td>
</tr>
<tr>
<td>遠地点 (km)</td>
<td>114,000</td>
<td>133,000</td>
<td>約100分</td>
</tr>
<tr>
<td>軌道周期</td>
<td>48時間</td>
<td>64時間</td>
<td></td>
</tr>
<tr>
<td>望遠鏡の有効面積 *1</td>
<td>1500×3台</td>
<td>800×1台</td>
<td>450×5台</td>
</tr>
<tr>
<td>空間分解能</td>
<td>6&quot;</td>
<td>0&quot;.5</td>
<td>&lt;90&quot;</td>
</tr>
<tr>
<td>エネルギー分解能 *2</td>
<td>3 (RGS)</td>
<td>60 (ACIS)</td>
<td>6 (XRS)</td>
</tr>
<tr>
<td>（eV）</td>
<td>3 (RGS)</td>
<td>60 (ACIS)</td>
<td>6 (XRS)</td>
</tr>
<tr>
<td>エネルギー分解能 *3</td>
<td>150 (EPIC)</td>
<td>150 (ACIS)</td>
<td>6 (XRS)</td>
</tr>
<tr>
<td>（keV）</td>
<td>RGS 0.35–2.5, EPIC 0.2–12</td>
<td>ACIS 0.4–10, LETG 0.1–6, HETG 0.6–10</td>
<td>XRS 0.4–10, XIS 0.4–10, HXD 10–600</td>
</tr>
</tbody>
</table>

*1 (cm²), @ 1keV
*2 (eV), @ 1keV
*3 (eV), @ 7keV

[裏へ続く]
Little Cooling Gas in Cores!

XMM-Newton Observations

- Little metal line emissions from low temperature gas
- This is the same for most clusters
  \[ \dot{M}_{\text{XMM}} \sim 0.1 \dot{M}_{\text{Classical}} \]

\[ (\dot{M}_{\text{Classical}} \propto \frac{L_{X,\text{Core}}}{kT}) \]
Something Stops Gas Cooling

Chandra observations

Gas cooling is stopped at $T \sim 1/2 \ T_{\text{out}}$

Inconsistent with the classical cooling flow model ($T \to 0$ as $r \to 0$)

6 clusters
(Allen, Schmidt & Fabian 2001)
Heating Sources

There must be heating sources to prevent cores from radiative cooling

Popular ideas

- AGNs (Tucker & Rosner 1983)
- Thermal conduction (Takahara & Takahara 1981)
AGNs

- AGN activities are often observed in cluster cores
  - Heating Source?

- Bubbles
  - AGNs in cluster cores can inflate bubbles of nonthermal plasma, which displace X-ray-emitting gas

Color: X-ray
Contours: Radio
(Blanton et al. 2001)
Problems of AGN Heating

Observation
- Gas temperature around the AGNs and bubbles is not large, etc.

Theory
- Generally, it is difficult to balance heating with cooling, etc.

Mixing by Bubble Motions?

- Bubbles move in the ICM via buoyancy
- The motions mix the surrounding ICM
  - Hot gas in outer regions is brought to the cluster center (heating)

Brüggen & Kaiser (2002)
Problems of Thermal Conduction

**Observation**
- Fine structures are often found in ICM
- Conduction rate must be low
  - If so, cores cannot be heated

**Theory**
- It does not work in low temperature clusters
  - Conduction rate $\propto T^{2.5}$

Vikhlinin, Markevitch & Murray (2001)
Problems

- **AGN**
  - Tuning between heating and cooling is very difficult
    - AGN’s power changes ~4 orders of magnitude
  - Thermal conduction
    - Conduction rate must be tuned
    - It is ineffective for low temperature clusters

- These problems have been recognized for a long time
  - Is it time to propose a new idea?
Tsunami Model

Collaborators

- Tomoaki Matsumoto (Hosei U.)
- Keiichi Wada (NAOJ)
- Takeru Ken Suzuki (Kyoto U.)
- Tae Furusho (JAXA)
Basic Idea

- In clusters, large scale bulk motions of gas should prevail
  - Large scale structure formation of the universe
- The bulk motions may affect the cluster cores
The origin of the bulk gas motions

- **Large scale structure of the universe**
  - Clusters are knots of filaments

- **Small clusters and galaxies fall into clusters along the filaments**
  - Velocity > 1000 km s$^{-1}$
  - Gas motions in the clusters

Circles are clusters (Borgani & Guzzo 2001)
Cosmological Numerical Simulations

- Velocity fields in the ICM of a cluster (Arrows)
  - $\geq 20$-$30\%$ of the sound velocity

Nagai et al. (2003)

Motl et al. (2004)
Tsunami Models

- Old Tsunami (One dimension)

- New Tsunami (Two dimension)
A cluster is spherically symmetric

Bulk gas motions are approximated by acoustic-gravity waves (‘tsunamis’)

These waves with relatively large amplitude eventually form shocks to shape sawtooth waves (N-waves)

- Shocks directly heat the surrounding ICM by dissipation of their wave energy

Analytical approach (weak shock theory)

Numerical simulation
Results of Analytical Approach

- Time independent
- Velocity amplitude
  - \( \sim 10\text{-}20\% \) of the sound velocity
- \( T, n_e \) profiles
- Comparison with observations
  - A1795
    - Ettori et al. (2002), Tamura et al. (2001)
  - Ser159-03
    - Kaastra et al. (2001)
- Consistent
- The core can be effectively heated
Results of One-Dimensional Simulations

- We needed to confirm the results of analytical approach
- Velocity perturbations of 10-20% of the sound velocity are given
- Cooling time is 2-∞ times increased, compared with the case of no waves
A Defect of One-Dimensional Study

- One-dimensional study showed that the bulk gas motions in a cluster could heat the core

- However, in the one-dimensional study, the heating efficiency could be overestimated

  - Waves are automatically focus on the cluster center
  - Multi-dimensional study is required
2D Hydrodynamic Simulations

- We focus on a cluster core
  - ≤300 kpc from the center
- Reproduction of fine structures
  - Nested grid code
  - Resolution of 22 pc at the center
- Gas cooling is included
- Gravitational potential is fixed (NFW)
- This is the first time to follow the evolution of the core in `a stormy cluster` with multi-dimensional high-resolution hydrodynamic simulations
Bulk Gas Motions

Plane waves are considered (Tsunamis)

Injection of waves
- ~300 kpc from the cluster center
- Wave velocity ($\alpha \times \text{sound velocity}$)
  - $\alpha = 0-0.5$
- Wave length ($\lambda$)
  - 100-1500 kpc

These parameters are based on results of cosmological numerical simulations
- e.g. Nagai et al. (2003), Motl et al. (2004)
Movie ($\alpha=0.3, \lambda=100$ kpc)

Temperature

Cluster Center

Filament of LSS

$\leq 200$ kpc

$\leq 20$ kpc (zoomed up)
Results 1

- Rayleigh-Taylor (RT) and Kelvin-Helmholtz (KH) instabilities
  - Formation of turbulence

Mechanisms
- The core cools through radiative cooling
- The core becomes denser
- Waves cannot move the core
- Relative motion between the core and the surrounding gas
- RT and KH instabilities
- Turbulence
Turbulence is spatially limited to the cluster core

- The turbulence does not completely erase metal abundance excess observed in cores

- If turbulence developed in the entire cluster, the excess would be erased

Fukazawa et al. (1994)
Typical cooling time of the core

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>(\lambda) (kpc)</th>
<th>(t_{\text{cool}}) (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>...</td>
<td>2.2</td>
</tr>
<tr>
<td>0.3</td>
<td>100</td>
<td>3.3</td>
</tr>
<tr>
<td>0.5</td>
<td>500</td>
<td>4.7</td>
</tr>
<tr>
<td>0.3</td>
<td>1000</td>
<td>6.2</td>
</tr>
<tr>
<td>0.3</td>
<td>1500</td>
<td>&gt;6.2</td>
</tr>
</tbody>
</table>

- We found an possible origin of turbulence that is responsible for core heating
Predictions

- The turbulence in a core should be developed only in cool cores (‘cooling flow clusters’)
  - If a core is not much cooled, waves pass the core without changing the structure
  - **No overheating**
    - Self-regulated
- The turbulent heating could work in groups of galaxies and elliptical galaxies
  - This is in contrast with heating through thermal conduction, which works only in high temperature clusters
    - Conduction rate $\propto T^{5/2}$
Structures of Dark Halos

- Dark matter structures are not much different between clusters and galaxies
  - Bulk gas motions and turbulence should be excited in smaller objects

Moore et al. (1999)
Comparison with Observations

- **Image**
  - Chandra, XMM-Newton

- **Spectra**
  - XMM-Newton, ASTRO-E2
Irregular Gas Distribution 1

Observations of Cluster Cores ($\approx 100$ kpc)

Centaurus (Sanders & Fabian 2002)

2A 0335+096 (Mazzotta et al. 2003)
Irregular Gas Distribution 2

- Cold Fronts (‘Sloshing’ type)
  - e.g. A1795 (Markevitch et al. 2001)

ZW3146
(Forman et al. 2003)
Our Predictions

- Turbulence creates very complicated structures
  - Not steady
- Filaments and cold fronts can be reproduced

\[ \leq 200 \text{ kpc} \]
\[ \leq 20 \text{ kpc (zoomed up)} \]
Can we observe the waves?

- Generally difficult
  - Wave amplitude is not large
  - Angle between wave fronts and the line of sight
- But yes

The core of A133 (Fujita et al. 2002, 2004)
ASTRO-E2

ASTRO-E2 will be launched in 2005

- Superb energy resolution
  - $\sim 100 \text{ km s}^{-1}$
- Metal lines can be investigated in detail
- We will be able to directly observe the velocity fields in the ICM for the first time

Bulk gas motion

- Doppler shift

Turbulence

- Doppler Broadening
Predicted X-ray Spectra

Centaurs Cluster

ASCA

ASTRO-E2
## Performance

<table>
<thead>
<tr>
<th></th>
<th>XRT-S + XRS</th>
<th>XRT-I + XIS</th>
<th>HXD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy range (keV)</strong></td>
<td>0.3 - 10</td>
<td>0.2 - 10</td>
<td>10 - 700</td>
</tr>
<tr>
<td><strong>Effective Area (cm²)</strong></td>
<td>180 (@6keV)</td>
<td>1300</td>
<td>160 (@2keV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>330 (@100 keV)</td>
</tr>
<tr>
<td><strong>Field of View</strong></td>
<td>2.9' x 2.9'</td>
<td>19' x 19'</td>
<td>0.56' x 0.56'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(&lt;80keV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.6° x 4.6°</td>
</tr>
<tr>
<td><strong>HPD of PSF</strong></td>
<td>1.9'</td>
<td>1.9'</td>
<td></td>
</tr>
<tr>
<td><strong>Number of pixels</strong></td>
<td>31</td>
<td>1024 x 1024</td>
<td></td>
</tr>
<tr>
<td><strong>Pixel Size</strong></td>
<td>29'' x 29''</td>
<td>1.1'' x 1.1''</td>
<td></td>
</tr>
<tr>
<td><strong>Energy resolution</strong></td>
<td>6 - 7 eV</td>
<td>120 eV (@6keV)</td>
<td></td>
</tr>
<tr>
<td>(FWHM)</td>
<td></td>
<td>3 keV (@20keV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10% @550keV</td>
<td></td>
</tr>
<tr>
<td><strong>Time resolution</strong></td>
<td>5 micro s</td>
<td>8ms - 8s</td>
<td>15.3 - 61 micro s</td>
</tr>
<tr>
<td><strong>Mission life</strong></td>
<td>2.4 - 3 years</td>
<td>as long as possible</td>
<td>as long as possible</td>
</tr>
</tbody>
</table>
高温プラズマの分光

地上の4keVプラズマ（電子ビームイオントラップ）からの放射（実データ）

- He-like Fe
- Li-like Fe

Temperature = 4keV
Integration time = 52.2 ks

床共役観測（2003年6月、9月）

Fe K emission line Astro-E2 XRS (simulation)

line broadening

\( \sqrt{v^2} = 90 \text{ km/s} \)

EBIT @ LLNL

by JAXA
Mock observations

- We summed up the spectra of individual computational grid points
  - This is the first time to construct detailed X-ray spectra from numerical simulation results
- ASTRO-E2 XRS response file is used
  - We made mock observations with ASTRO-E2
  - Fe lines at $\sim$6.7 keV
Results

Black: Tsunami
Red: No Tsunami

- Fe lines are broadened by turbulence
- Lines are shifted by tsunamis
  - Bulk motion of the cluster core
  - Asymmetric injection of waves (e.g. cluster mergers)
  - Line shifts are unlikely to occur for turbulence induced by symmetric jets accompanied by AGN activities
Summary

Cooling flow problem

- Little cooling gas has been observed in cluster cores
- There must be a heating source in a cluster core

Popular solutions

- AGNs
- Thermal conduction
- Both have serious problems
Summary

- **Tsunami model**
  - Hierarchical clustering scenario predicts bulk gas motions in clusters
  - The cores should be affected by the motions

- **Two-dimensional simulations showed that local but strong turbulence is created in a core**
  - The turbulence suppresses radiative cooling
  - Complicated X-ray structures observed in cores can be reproduced
  - Turbulence could be observed with ASTRO-E2
The Future

- **3D ultra-high resolution cosmological simulations**
  - Structure of turbulence is different between 2D and 3D
  - Heat transfer could be more efficient in 3D turbulence
  - Wave injection from various directions
  - Change of gravitational potential well

- **Particle acceleration by turbulence**
  - Radio mini-halos?

- **Magnetic fields**
  - Amplification of magnetic fields
  - Thermal conduction

- **Turbulent dissipation**