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# The simulation of cooling flows in clusters of galaxies

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Chapter 7

# Conclusion and Remarks

## 7.1 Conclusion

This work is a study of the cooling flow problem in clusters of galaxies. In many clusters, the gas density is sufficiently high in the central regions, that the cooling timescale, as usually estimated, is less than the Hubble time. This suggests that the gas should be cooling and flowing inward; there should be evidence for cool gas in the core of these clusters. This, indeed, is a unavoidable prediction of the standard cooling flow model.

The current cooling flow problem is the discrepancy between this prediction and the recent X-ray observations with high spectral resolution. The standard cooling flow model predicts a large quantity of cool gas which is not observed in current X-ray observations. Therefore, much attention has been given to additional heating sources such as active galactic nuclei. The principal conclusion of this thesis is that the resolution of the problem may well lie in unrealized assumptions of the standard cooling flow model; that extra heating sources may not be necessary.

This point has been addressed in the various chapters as outlined here:

**1 -** In chapter 1, I introduce the subject and and review the cooling flow problem in cluster of galaxies.

**2 -** In chapter 2, the most relevant observed X-ray properties of galaxy clusters are given:

① From modern X-ray instruments (Chandra and XXM-Newton), the temperature profile in clusters of galaxies is found to decline outward with the radius; i.e., the gas is not isothermal as previously thought. This new result has an important impact on the mass determination of clusters from X-ray data. Moreover, in cooling flow clusters, below some radius, the temperature declines towards the cluster center, apparently due to the cooling. In other words, in cooling flow clusters, there is a break radius. Within this break radius, the temperature gradient is positive, and beyond, the temperature gradient is negative (see Fig. 2.2) In general, the core of cooling flow clusters is characterized by a temperature drop in the core and a high central X-ray surface brightness.

② The multi-phase medium is ruled out. Most of the X-ray observations of galaxy clusters suggests a single phase medium (one single temperature and density at every point). The importance of this result is that the multi-phase standard cooling flow model can no longer be considered valid.

③ In non-cooling flow clusters, the metallicity is constant with the radius, at nearly one-third solar metallicity. But, in cooling flow clusters, the metallicity is peaked toward the cluster center within the cooling radius. Outside the cooling radius , the metallicity is a constant at near one-third solar metallicity as in the non-cooling flow clusters. This means the cooling flow has an important effect in the metallicity distribution.

**3 -** In chapter 3 and chapter 4, I have concentrated on the discrepancy between multiphase standard cooling flow model and the X-ray observations. Moreover, I have investigated in detail the assumptions of the standard cooling flow model, specifically in the following respects:

① The cooling flow problem is mainly due to the steady flow assumption in the standard cooling flow model.

② In cooling flow clusters, spherically symmetric steady flow in the absence sinks means that mass flow rate is zero at each radius; this means that there is no flow at all. In the standard cooling flow model, a non-zero constant mass flow rate requires additional assumptions: (i) the gas must accumulate near the center of clusters, or (ii) the gas must drop out of the flow over an extended region. There is no additional physical motivation for these constraints.

③ The multiphase idea (many gas temperatures and densities at each radius) is a consequence of the implied the mass drop out. However, the mass drop out phase is non-gaseous (from continuity equations) which can not be seen at X-ray frequencies.

④ The mass flow rate - X-ray luminosity relationship, derived from the internal energy equation, differs from that derived in the context of the standard model using the first law of thermodynamics. In the standard derivation, the total flux of internal energy through a given radius is ignored.

⑤ The isobaric cooling time scale, based on the steady flow assumption (or a density which does not vary with time) may be very different in a general non-steady flow. Because matter and heat flow inward, the cooling timescale could, in fact, be much longer.

**4 -** In chapter 5, I describe simulations of non-steady gas flow, with only radiative cooling, in clusters of galaxies.

These simulations are relevant to unsteady flow; it is found that the mass flow rate depends linearly on radius in contrast to the standard cooling flow assumptions. In the standard cooling flow model, the linear relation is explained by proposing a steady multi-phase or inhomogeneous flow. We argue that the linearity of the flow rate with radius is typical for any unsteady subsonic cooling flow.

② For unsteady flow, the specification of initial conditions is extremely important for the subsequent development of the flow. Assuming an NFW cold dark matter density profile, the initial temperature distribution of the gas is the most relevant initial condition. For example, the assumption of an isothermal gas and hydrostatic equilibrium requires a steep gas density distribution which leads to catastrophic cooling in the very central region after a relatively short interval of time (short compared to the Hubble time). With a more realistic, radially declining initial temperature profile (Loken et al. 2002), the interval of time required for catastrophic cooling can approach the Hubble time.

③ Simulations relevant to the state of flow in three clusters, A2050, NGC533 and MKW 3s, have been carried out. The simulated time scale for these simulations is 9 Gy. We find that at the end point of these simulations the calculated temperature profile fits the observations of the present temperature distribution without any additional heating sources.

④ For two of the clusters, A2052 and MKW3s, catastrophic cooling does occur in the central few cells after 9.3 Gy and 8.1 Gy respectively. In the case of A2052, higher resolution calculations reduce the volume of the region over which the catastrophic cooling occurs (from 150 pc to 12 pc) strongly implying that the effect is largely numerical. If there really is physical catastrophic cooling in such a small region, a heating source can not solve this problem. A heating source such as AGNs will heat the entire cooling core which means that the heating mechanism must be fined-tuned to heat the very central regions. The mass flux in the rapidly cooling region is not large enough to supply the energy source for heating (feedback) via the AGN phenomenon.

⑤ Thermal conduction can play an important role in suppressing cooling near the center, especially at the beginning of the simulations when the temperature is still high and its gradient is positive (increasing temperature with radius). This would apparently be true even in the presence of a tangled magnetic field because of the large suppression factor required.

⑥ The mass flow rate in the context of the standard model, from the luminosity-flow rate relationship, is roughly equal to the actual mass flow rate (in the simulations) within the cooling radius.

**5 -** In chapter 6, I describe simulations of non-steady gas flow, with effervescent heating mechanism and radiative cooling, in clusters of galaxies.

① The best fit with the observations is the model with cooling only. The simulated cluster fit the observation until time 7.2 Gyr.

② The effervescent heating mechanism can not balance the radiative cooling. In higher resolution simulation, the heating is not enough to balance the cooling.

③ the effervescent heating model is not physically correct but it is artificial model and it can reflect the effect of heating by AGNs.

④ The heating increases the cooling time scale which is not observed. In most of the cooling flow clusters, the observed cooling time scale is very short which is against the heating of clusters.

The most important conclusion of this thesis is that the perceived cooling flow problem in clusters of galaxies is primarily due to the assumption of steady flow in the standard cooling flow model. When this assumption is relaxed, and the gas density profile is allowed to evolve in a realistic way, it appears to be no cooling flow problem.

## 7.2 Future Work

Many astrophysical topics and computational techniques for hydrodynamical simulations remain to be considered:

❶ The large scale behavior of plasma plays an important role many astrophysical contexts. Correct plasma simulations require multi-fluids simulations with appropriate physics. All astrophysical gas dynamical simulations to date consider only single fluid. An immediate goal is to develop the FLASH code in order to simulate the dynamics of multi-fluids with different velocities, gas densities and temperatures.

❷ The current astrophysical plasmas magnetohydrodynamics simulations assume that the plasma is neutral and that the ions and electrons move with the same velocity. It is important to generalize to the case where the different fluid components can move with different velocities; this will change the physics of the plasma and very possibly introduce instabilities. Multi-fluid simulations are necessary to consider this problem.

❸ It is important to develop new diagnostic techniques for viewing the results of numerical models. For example, one may assume an initial model of the gas density and temperature distribution in a cluster and then convert it to an observed form (e.g. intensity distribution), using the techniques of an X-ray instrument. This can be more directly compared to X-ray observations carried out with the same instrument. That is important because it requires a close cooperation between theorists and observers and is likely to lead to a better understanding of the physics of the system (for example, the possible effect of deviations from spherical symmetry). Another example is provided by the observed X-ray cavities (dark regions) inside the high X-ray surface brightness regions, which implies that the AGNs inflate bubbles (cavities) while heating the ICM. The difficulty with this interpretation is that the cavities are very low surface brightness regions or holes and are buried in very hot plasma with high X-ray surface brightness. The simulations of X-ray observations which I suggest here can test this interpretation.

❹ The process of cluster mergers plays an important role in the formation, evolution, and properties of clusters. For example, X-ray and weak lensing observations of the now famous "bullet" cluster (Clowe et al. 2006) demonstrate the importance of gas dynamical processes in determining the distributions of gas and dissipationless components in a merging cluster. This is a very fruitful problem for 3D hydrodynamical simulations of clusters. Simulations are required in order to understand the merger process in clusters of galaxies.