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The simulation of cooling flows in clusters of galaxies

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The cooling flow problem is due to un-realistic
assumptions of standard cooling flow model.

Chapter 1

Introduction: The Cooling flow problem in Clusters of Galaxies.

1.1 Introduction

Galaxy clusters are the largest objects in the universe which are virialized, which can be well assessed by observation and well described by theoretical models. With these properties they also form the largest astrophysical laboratories, in which the physical environmental conditions can be well observed and described. They consist of dark matter, hot plasma and galaxies together, roughly in proportions of 87% , 11% and 2% (Böhringer 2004).

The intra-cluster medium (ICM) is hot and optically thin. The ICM has mean temperature in the range of $kT = 0.5 - 15$ keV, (1 keV $= 1.16045 \times 10^7$ K). The gas density varies from $\sim 10^{-4}$ cm^{-3} in the outer regions of clusters to a few 10^{-2} cm^{-3} in the center (Arnaud 2005).

The X-ray emission from clusters of galaxies is primarily due to thermal Bremsstrahlung or free-free emission from the fully ionized plasma. Because this is a collisional process the volume emissivity (the power of emitted radiation per unit volume) is proportional to the square of the electron density. Since the thermal energy content of the gas is proportional to the electron density, this means that the cooling timescale is inversely proportional to the electron density. Within the 100 kpc or so of the center of most clusters of galaxies, the electron density is high enough that this radiative cooling time of the gas, due to the emission of X-rays, is less than the age of the clusters ($\approx 10^{10}$ yr). Therefore, the radiating gas must cool and flow inward (subsonically) in order to maintain the pressure required to support the weight of the overlying gas. This subsonic flow is known as a cooling flow (Fabian & Nulsen 1977; Cowie & Binney 1977) and the centers of clusters with $t_{cool} < H_o^{-1}$ are known as "cooling flow clusters", even though there is no direct evidence for either cooling or flowing (see Donahue & Voit 2004 for review). The cooling region, i.e., the region within which $t_{cool} < H_o^{-1}$, is called as a cooling core with high X-ray surface brightness.

1.2 The cooling flow problem in clusters of galaxies

When it was first realized that the gas in the central regions of clusters should cool and flow inward, a simple model, the standard cooling flow model, was developed. The principal assumption and the heart of standard cooling flow model is the assumption of steady flow; this means that the partial time derivative of the gas density and velocity is equal to zero everywhere [1]. In other words, the gas density profile does not change with the time, and the gas mass is constant during the cooling. The main problem with this assumption is that, given spherical symmetry, the flowing gas must accumulate somewhere near the center, and this is not observed. From the continuity equation with the steady flow assumption, the mass flow rate (i.e., the inflowing mass which enters a sphere of radius r per unit time) is constant with the radius and does not evolve. This standard model, in its original form, involved a single gas phase– density and temperature– at every point; we will refer to this original form as the "simple cooling flow model". It can be demonstrated from straightforward arguments, involving the first law of thermodynamics, that the mass flow rate is proportional to the X-ray luminosity divided by the gas temperature (see Chapter 3). That is to say, one can determine the mass flow rate directly from X-ray observations. It was found that the X-ray observations are not consistent with the simple form of the standard cooling flow model. The standard model with steady flow and single phase implies a higher central surface brightness than observed (Fabian et al. 1984). The observations imply (via the luminosity-flow rate relation) that the gas mass flow rate is proportion to radius ($\dot{M} \propto r$) (Peres et al. 1998) and not constant. The simple cooling flow model therefore fails to describe the X-ray observations.

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If the flow rate is proportional to radius, as implied by the X-ray observations, and is at the same time steady flow, then, from the continuity equation, there must be a drop out of mass from the gas phase throughout the cooling core. This drop out is called a mass deposition or gas sink within the cooling radius. For the steady flow assumption, the mass deposition rate is equal to the mass flow rate, and therefore can be determined by X-ray observations as well. That implies that the gas is a multi-phase medium; i.e. there are many gas densities and temperatures at each radius, moving inward together with the same flow velocity (Thomas 1987; Johnstone et al. 1992). Therefore, the necessity of a multi-phase medium becomes a fundamental ingredient of the standard cooling flow model. Without it the model fails , but it is important to realize that this is a mechanism applied to keep the gas in steady state and fit the observations at the same time; there is no additional physical motivation. The standard model, beyond its simple form, is thus characterized by inhomogeneity and presence of a

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[1] In section 4.2 in page 49,we will see that the cooling flow problem is due to that assumption and it is impossible assumption in any cooling system with gravity. That is a one of most important result in my thesis

significant quantity of cool gas inside cooling radius. Older X-ray observations with low spectral resolution, i.e., prior to the XMM-Newton and Chandra X-ray observatories, showed that the ICM is a multi-phase flow, in agreement with the standard cooling flow model. That is to say, the X-ray flux could be fitted by a wide rage of temperatures at each radius. For example, the EINSTEIN Crystal Spectrometer and Solid State Spectrometer observations of the M87 halo supported the existence of a multi-temperature gas at each radius as expected for the standard cooling flow model (Canizares et al. 1979, 1982; Mushotzky & Szymkowiak 1988).

Early estimates, based upon all these arguments, implied a mass flow rate or the mass deposition rate between 10 - 1000 $M_{\odot}$/yr (see Fabian 1994 for review). Moreover, the mass flow rate- X-ray luminosity relationship implies that matter drops out of the flow over a large region such that the remaining mass flow rate varies as $\dot{M} \propto r$. This has become a fundamental aspect of what is called the "multi phase standard cooling flow model or standard cooling flow model." But what is the fate of this gas which drops out of the flow? This cooling gas should be observable at some other wavelength– optical emission lines or evidence of on-going star formation– but this evidence has always been missing or unconvincing. This problem was traditionally known as mass sink problem or cooling flow problem. For example, McNamara (1997) demonstrated that the star formation rates are only in range of 1 % to 10% of the mass deposition rate inferred from X-ray observations. Edge (2001) concluded, from of CO line emmision in 16 cooling flow clusters, that the masses in the observed clouds are only factor 5-10% of that expected to have been deposited in these cooling flows.

This was the original cooling flow problem, and it is important to realize that the problem arises from the conflict between the interpretations of X-rays observations and the observations at other wavelengths. The problem was the fate of cooling gas, which should be present according to standard model, but is not observed.

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The nature of cooling flow problem changed at the end of 1999 with the advent of high spatial and spectral resolution data from Chandra and XMM Newton: there is no evidence (from X-ray observations) of any gas cooling below $1-2$ keV (Kaastra et al. (2002); Peterson et al. (2003); Tamura et al. (2001)). Moreover, the observed temperature profiles can be fitted well with a single temperature model . Matsushita et al. (2002), from XMM data for M 87 halo (ICM was supposed to be multi-phase), have shown that the temperature structure is well described by a single temperature model. These new X-ray observations are implying that the ICM is not cooling over wide range of temperature as required in the context of the standard model (Molendi & Pizzolato 2001).

The essential puzzle perceived to be added by the new observations is this: Why does the gas stop cooling any further below one half to one third of ambient temperature even thought the isobaric cooling time scale is very short in the center? This is the new cooling flow problem and it arises from X-ray observations only– not the expectation of cool gas seen at other wavelengths. But, in a sense, this can be seen as a discrepancy between the new X-ray observations and the standard model. In the context of standard model, the cooling must be suppressed; i.e., the ICM needs to be heated and a current popular mechanism is the sporadic heating by active galactic nuclei (AGN) in the centers of cooling flow clusters.

In fact, the new observations are not as surprising as thought because the X-ray observations now agree with observations of other wavelengths– i.e., no evidence for cool gas. The problem, in fact, lies with the assumptions of the standard model, specifically with those of steady state flow and isobaric cooling.

The strong discrepancy between standard cooling flow model and current X-ray observations indicates either that the gas is prevented from cooling by some heating mechanism or that the steady flow assumption of standard cooling flow model is not realized and it is not appropriate for ICM. In this dissertation I will show why standard cooling flow model fails physically and observationally (the ICM is not steady and homogeneous). Moreover I will discuss in more detail the standard cooling flow model and derive its main components (the cooling time scale, mass flow rate and inhomogeneous cooling spectra) from equations of hydrodynamics and test the main assumptions from simulations, only with cooling. And finally I will show the amount of cool gas depends essentially on initial conditions, especially the initial gas temperature profile. In other words, the cooling flow depends upon the initial state of the gas.

1.3 Thesis organization

The organization of this thesis is as follow:

- In chapter 2, I will review the physical properties of galaxy clusters as implied by the X-ray observations. These properties, such as the gas temperature and density profiles, are important for determining the thermodynamic state of the hot gas and the cooling by X-ray emission.

- In chapter 3, The properties of the standard cooling flow model, cooling flow time scale, the mass flow-X-ray relationship, and the cooling flow spectra will be derived, using the hydrodynamics equations.

- In chapter 4, I will consider the validity of the standard cooling flow model via the equations of hydrodynamics. I will critically consider the main assumption of standard cooling flow model steady flow, and its consequences for the cooling flow problem. I suggest that a relaxation of the steady flow assumption can be the solution of the cooling flow problem and will show that it is not straightforward to determine the cooling time scale in non-steady flow.

- In chapter 5, I describe the results of hydrodynamical time-dependent 1d-simulations, with only cooling using the FLASH code. I have applied realistic initial conditions assuming the hydrostatic equilibrium in potential generated by the NFW dark matter profile and the universal temperature profile of for the hot gas Loken et al. (2002). The standard cooling flow model will be tested through these simulations. The aim of this chapter to study the effect of pure radiative cooling on cluster properties. I demonstrate that the observed temperature profile of clusters of galaxies can be matched by these simulations without any additional heating source.

- In chapter 6, the heating process will be studied through hydrodynamical time-dependent 1d-simulations. The aim of this chapter is to study the suppression of cooling by a heating source in clusters of galaxies. We have used the AGN spherically symmetric heating model as a heating source; this is a mechanism resulting from the inflation of bubbles through the ICM. It is called the effervescent heating (Begelman 2001). The heating flux in this model depends on the gas pressure gradient. However, the physics of inflation of bubbles is still unclear. Moreover, not every cooling flow cluster has observed bubbles or X-ray cavities.

- In chapter 7, I summarize the essential results of this thesis and propose future work.