Synopsis

According to the hierarchical structure formation model, massive structures like galaxy clusters are formed due to the gravitational collapse of initial density perturbations and their subsequent mergers. As the formation of galaxy clusters is driven by gravity, they are expected to follow self-similar profiles for density, temperature, entropy etc (Kaiser 1986). However, observations show that self-similarity assumption is not followed in clusters due to the presence of cooling and other such non-gravitational processes (Markevitch et al. 1998; Ponman et al. 1999). More than a third of galaxy clusters have cooling time of the hot diffuse gas in the intra-cluster medium (ICM) in their core smaller than their lifetime (Cavagnolo et al. 2009). As a result, the hot gas in cluster core is expected to cool down catastrophically with total cold gas mass deposition in the core greater than 10^{12} $M_{\odot}$ during their lifetime and a star formation rate of several 100 $M_{\odot}yr^{-1}$. However, lack of observational support of these cooling flow signatures (Peterson et al. 2003) in clusters with short cooling time (cool core clusters) point to the presence of some heating mechanism to compensate the cooling loses and prevent the runway cooling. Among many possible candidates, AGN jets associated with the supermassive black hole present in member central galaxy of the cluster has emerged as the principle heating source (McNamara and Nulsen 2007). Observations show that the energy required to form the structures in the ICM as a result of AGN outbursts, are sufficient to overcome the radiative losses of the ICM. However, the details of AGN feedback to control the cooling flow remains sketchy. My thesis is based on numerical study of AGN feedback in galaxy clusters and trying to answer some important questions related to it.

In chapter 1, we discuss the process of galaxy cluster formation and how self-similarity arises naturally in such systems. We then discuss the observational evidences of the breaking of self-similarity in galaxy clusters. We look at the early history of X-ray observations of galaxy

clusters and the quest to find signatures of cooling flow as predicted by theoretical models. The non-detection of cooling flow signatures like absence of line emissions below 0.5 keV in several cool core clusters gave rise to the possibility of presence of some heating mechanism to control the cooling flow. We discuss the observational evidences pointing to AGN jets being the possible heating source to compensate for the cooling losses of the ICM. We discuss the different modes of AGN feedback in galaxy clusters and their role in the evolution of these systems. We finally give a brief history of the numerical work done in the area of AGN feedback in galaxy clusters. This chapter ends with the big questions in AGN feedback model that needed investigation.

In chapter 2, using high-resolution 3-D and 2-D (axisymmetric) hydrodynamic simulations in spherical geometry, we study the evolution of cool cluster cores heated by feedback-driven bipolar active galactic nuclei (AGN) jets. Condensation of cold gas, and the consequent enhanced accretion, is required for AGN feedback to balance radiative cooling with reasonable efficiencies, and to match the observed cool core properties. A feedback efficiency (mechanical luminosity $\approx \epsilon \dot{M}_{\rm acc} c^2$; where $\dot{M}_{\rm acc}$ is the mass accretion rate at 1 kpc) as small as 6×10^{-5} is sufficient to reduce the cooling/accretion rate by ~ 10 compared to a pure cooling flow in clusters (with $\mathrm{M}_{200} \lesssim 7 \times 10^{14}\ \mathrm{M}_\odot$). This value is much smaller compared to the ones considered earlier, and is consistent with the jet efficiency and the fact that only a small fraction of gas at 1 kpc is accreted on to the super-massive black hole (SMBH). The feedback efficiency in earlier works was so high that the cluster core reached equilibrium in a hot state without much precipitation, unlike what is observed in cool-core clusters. We find hysteresis cycles in all our simulations with cold mode feedback: *condensation* of cold gas when the ratio of the cooling-time to the free-fall time ($t_{\rm cool}/t_{\rm ff}$) is $\lesssim 10$ leads to a sudden enhancement in the accretion rate; a large accretion rate causes strong jets and *overheating* of the hot ICM such that $t_{\rm cool}/t_{\rm ff} > 10$; further condensation of cold gas is suppressed and the accretion rate falls, leading to slow cooling of the core and condensation of cold gas, restarting the cycle. Therefore, there is a spread in core properties, such as the jet power, accretion rate, for the same value of core entropy or $t_{\rm cool}/t_{\rm ff}$. A fewer number of cycles are observed for higher efficiencies and for lower mass halos because the core is overheated to a longer cooling time. The 3-D simulations show the formation of a few-kpc scale, rotationally-supported, massive ($\sim 10^{11}\mathrm{M}_\odot$) cold gas torus. Since the torus gas is not accreted on to the SMBH, it is largely decoupled from the feedback cycle. The radially dominant cold gas ($T < 5 \times 10^4$ K; $|v_r| > |v_\phi|$) consists of fast cold gas uplifted by AGN jets and freely-infalling cold gas condensing out of the core. The radially dominant cold gas extends out to 25 kpc for the fiducial run (halo mass $7 \times 10^{14} \mathrm{M}_\odot$ and feedback efficiency 6×10^{-5}), with the average mass inflow rate dominating the outflow rate by a factor of ≈ 2. We compare our simulation results with recent observations.

In chapter 3, we investigate the stochastic condensation of cold gas and its accretion onto the central super-massive black hole (SMBH) which is essential for active galactic nuclei (AGN) feedback to work in the most massive galaxies that lie at the centres of galaxy clusters. Our 3-D hydrodynamic AGN jet-ICM (intracluster medium) simulations, looking at the detailed angular momentum distribution of cold gas and its time variability for the first time, show that the angular momentum of the cold gas crossing $\lesssim 1$ kpc is essentially isotropic. With almost equal mass in clockwise and counter-clockwise orientations, we expect a cancellation of angular momentum on roughly the dynamical time. This means that a compact accretion flow with a short viscous time ought to form, through which enough accretion power can be channeled into jet mechanical energy sufficiently quickly to prevent a cooling flow. The inherent stochasticity, expected in feedback cycles driven by cold gas condensation, gives rise to a large variation in the cold gas mass at the centres of galaxy clusters, for similar cluster and SMBH masses, in agreement with the observations. Such correlations are expected to be much tighter for the smoother hot/Bondi accretion. The weak correlation between cavity power and Bondi power obtained from our simulations also match observations.

Recent analysis shows that it is important to explicitly include the gravitational potential of the central brightest central galaxy (BCG) to infer the acceleration due to gravity (g) and the free-fall time ($t_{\rm ff} \equiv [2r/g]^{1/2}$) in cool cluster cores. Accurately measuring $t_{\rm ff}$ is crucial because according to numerical simulations cold gas condensation and strong feedback occur in cluster cores with $\min(t_{\rm cool}/t_{\rm ff})$ below a threshold value close to 10. Recent observations which include the BCG gravity show that the observed threshold in $\min(t_{\rm cool}/t_{\rm ff})$ lies at a somewhat higher value, close to 10-30; there are only a few clusters in which this ratio falls much below 10. In chapter 4, we compare numerical simulations of feedback AGN (Active Galactic Nuclei) jets interacting with the intracluster medium (ICM), with and without a BCG potential. We find that, for a fixed feedback efficiency, the presence of a BCG does not significantly affect the temperature but increases (decreases) the core density (entropy) on average. Most importantly, $\min(t_{\rm cool}/t_{\rm ff})$ is only affected slightly by the inclusion of the BCG gravity. Also notable is that

the lowest value of $\min(t_{\rm cool}/t_{\rm ff})$ in the NFW+BCG runs are about twice larger than in the NFW runs because of a shorter time for feedback heating (which scales with the free-fall time) in the former. We also look at the role of depletion of cold gas due to star formation and show that it only affects the rotationally dominant component (torus), while the radially dominant component (which regulates the feedback cycle) remains largely unaffected. Stellar gas depletion also increases the duty cycle of AGN jets. The distribution of metals due to AGN jets in our simulations is predominantly along the jet direction and the radial spread of metals is less compared to the observations. We also show that the turbulence in cool core clusters is weak, consistent with recent *Hitomi* results on Perseus cluster.