Cool gas accretion, thermal evaporation and quenching of star formation in elliptical galaxies

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The most evident features of colour-magnitude diagrams of galaxies are the red sequence of quiescent galaxies, extending up to the brightest elliptical galaxies, and the blue cloud of star-forming galaxies, which is truncated at a luminosity \( L \sim L_* \). The truncation of the blue cloud indicates that in the most massive systems star formation must be quenched. For this to happen the virial-temperature galactic gas must be kept hot and any accreted cold gas must be heated. The elimination of accreted cold gas can be due to thermal evaporation by the hot interstellar medium, which in turn is prevented from cooling by feedback from active galactic nuclei.

1 Need for quenching of star formation in galaxies

Colour-magnitude diagrams of galaxies are dominated by the red sequence of quiescent galaxies and the blue cloud of star-forming galaxies (Blanton et al. 2003, Baldry et al. 2004), with a green valley in between, in which a minority of galaxies lie (Driver et al. 2006). While the red sequence extends up to the bright end of the galaxy distribution, the blue cloud is truncated at a luminosity \( L \sim L_* \), so there are not very massive blue, star-forming galaxies. Such a feature can be reproduced in galaxy formation models only assuming that star formation is effectively quenched in the galaxies with the deepest potential wells (e.g. Bower et al. 2006; Croton et al. 2006; Cattaneo et al. 2008). What are the processes responsible for this quenching is still matter of debate.

For star formation to cease in a galactic system, it is necessary that (1) hot (virial-temperature) gas does not cool efficiently and (2) accreted cool gas is heated before it can form stars (Binney 2004). Task (1) can be accomplished by feedback from Active Galactic Nuclei (AGN). Though the details of how AGN feedback works are controversial, empirical evidence that this mechanism is effective comes from studies of cool cores in galaxy clusters (Birzan et al. 2004; McNamara & Nulsen 2007), suggesting that also in massive galaxies virial-temperature gas is kept hot by the intermittent jets of the central radio source (Binney 2004; Nipoti & Binney 2005). Other mechanisms, such as gravitational heating by clumpy accretion (Dekel & Birnboim 2008, Khochfar & Ostriker 2008), can contribute to prevent virial-temperature gas from cooling, but non-gravitational heating is necessary to drive gas out of the galaxy potential.

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2 Quenching by thermal evaporation in \( L > L_* \) elliptical galaxies

An important difference between very massive elliptical galaxies and less massive galaxies is that the former are hot-gas rich, in the sense that they contain large amounts of relatively dense, X-ray emitting, virial-temperature gas, while the latter are hot-gas poor, in the sense that their diffuse X-ray emission is hardly detectable (lower mass elliptical galaxies; e.g. David et al. 2006) or not detected at all (disc galaxies; e.g. Rasmussen et al. 2009). This means that in lower-mass galaxies the virial-temperature gas halos, which are expected to exist on theoretical grounds, are very rarified.

These observational findings are reasonably well understood theoretically, in terms of the existence of a critical dark-matter halo mass \( M_{\text{crit}} \sim 10^{12} M_\odot \). Only in halos with mass above \( M_{\text{crit}} \) a significant fraction of the primordial infalling gas is shock heated to the virial temperature (Binney 1977; Birnboim & Dekel 2003; Kereš et al. 2005; Dekel
and the gravitational potential wells are deep enough to retain gas heated by supernova feedback (Dekel & Silk 1986). As a consequence, denser and denser hot-gas atmospheres build up only in systems with mass $M \gtrsim M_{\text{crit}}$, while $M \lesssim M_{\text{crit}}$ systems are expected to have very rarefied coronae of virial-temperature gas.

Let us consider the process of cool gas accretion onto galaxies as a function of the galaxy total mass $M$ or virial temperature $T_{\text{vir}}$. Infalling cool ($T \ll T_{\text{vir}}$) clouds find very different physical conditions, depending on whether the accreting galaxy has total mass higher or lower than $M_{\text{crit}}$. If $M \gtrsim M_{\text{crit}}$, the cool clouds are likely to be eliminated by ablation and thermal evaporation because of the high temperature and relatively high density of the hot interstellar medium (Binney 2004; Nipoti & Binney 2004), while cool clouds are likely to survive if $M \lesssim M_{\text{crit}}$. Nipoti & Binney (2007) explored this problem quantitatively, by calculating the minimum rate of ablation with a simple model based on analytic estimates of the evaporation rate (Cowie & McKee 1977; Cowie & Songaila 1977; McKee & Cowie 1977). Cool gas clouds less massive than a minimum mass $M_{\text{min}}$ are evaporated by thermal conduction before they can form stars. Though the estimate of $M_{\text{min}}$ is affected by the uncertainties on the suppression of thermal conduction by tangled magnetic fields, the ratio of $M_{\text{min}}$ in different systems is a robust quantity. The minimum mass of clouds that can survive evaporation in a representative hot-gas rich, very massive ($M > M_{\text{crit}}$) galaxy is a factor of $\sim 1000$ larger than in a representative hot-gas poor, less massive ($M < M_{\text{crit}}$) galaxy, even though the mass ratio between the galaxies is just a factor of 10. As a consequence, the aggregate mass of gas available for star formation, per unit galaxy mass, is a factor of $\sim 10$ larger in the low-mass system than in the high-mass system (see Nipoti & Binney 2007 for details). The bottom line is that thermal evaporation of cool clouds by the hot interstellar medium can give an important contribution to quench star formation in the most massive elliptical galaxies ($L > L_*$).

3 What about $L < L_*$ galaxies?

We have seen that thermal evaporation can explain the truncation of the blue cloud at $L \gtrsim L_*$. At luminosities $L \lesssim L_*$, we find galaxies in both the red sequence and the blue cloud. All these systems have galactic dark-matter halos with masses $\lesssim M_{\text{crit}}$, relatively low virial temperature and quite rarefied hot-gas atmospheres. Therefore, according to the results of Nipoti & Binney (2007), thermal evaporation is not efficient and star formation can proceed as long as cool gas is accreted.

So what determines whether a $L < L_*$ galaxy lies in the blue cloud or in the red sequence? It seems likely that the key factor is environment: the fraction of galaxies in the red sequence is observed to increase for increasing density of the environment (from voids to clusters), and the effect is stronger for lower-mass galaxies (Baldry et al. 2006). This trend can be explained by considering that a $L < L_*$ galaxy belonging to a big group or a cluster has little chance of accreting cool gas, which can be easily eliminated via a combination of ram-pressure stripping and thermal evaporation by the hot intracluster medium. However, in contrast with the brightest elliptical galaxies, it is not excluded that $L < L_*$ elliptical galaxies have experienced small recent episodes of star formation, if they happened to accrete some cool gas. This accounts for the fact that lower-luminosity ellipticals have cusplier central luminosity profiles and younger central stellar populations than the most luminous ellipticals (Nipoti & Binney 2007; Nipoti 2009).

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