*SF2A 2017*
*C. Reylé, P. Di Matteo, F. Herpin, É. Lagadec, A. Lançon, Z. Meliani, F. Royer (eds)*

# QUENCHING OF THE STAR FORMATION ACTIVITY OF GALAXIES IN DENSE ENVIRONMENTS

A. Boselli[1]

**Abstract.** The nearby Universe is an ideal laboratory to study the effects of the environments on galaxy evolution. We have analysed the multifrequency properties of galaxies in the nearby clusters Virgo, Coma, and A1367. We have shown that the HI gas content and the activity of star formation of the late-type galaxies start to gradually decrease inwards $\sim$ one virial radius. We have also shown that late-type galaxies in these clusters have truncated HI, $H_2$, dust, and star forming discs once the HI gas content is removed by the harsh environment. Some of these galaxies also exibit spectacular tails of atomic neutral, ionised, or hot gas without any counterpart in the stellar component. All this evidence favors ram pressure stripping as the dominant mechanism responsible for the gas removal from the disc, and for the following quenching of the star formation activity.

Keywords: Galaxies: evolution, galaxies: interactions, galaxies: ISM, galaxies: star formation

## 1 Introduction

It is now well established that the main drivers of galaxy evolution are the total mass of galaxies (Cowie et al. 1996; Gavazzi et al. 1996; Boselli et al. 2001) and the environment in which galaxies resides (Boselli & Gavazzi 2006, 2014). The simple analysis of a colour-magnitude relation done on a large sample of local objects indicates that galaxies form two main sequences, one composed of red passive objects and one of blue star forming systems. The fraction of red objects increases with increasing stellar mass of the system and with the density of objects within the Universe (Peng et al. 2010; Gavazzi et al. 2010).

Different physical processes have been invoked to explain this observational evidence. Merging (e.g. Kauffmann et al. (1993)), AGN feedback (e.g. Kauffmann et al. (2003)), or secular evolution (Gavazzi et al. 1996; Boselli et al. 2001; Boissier & Prantzos 2000; Boissier et al. 2001), including the modulation induced by bars on the star formation activity of rotating systems (Gavazzi et al. 2015; Consolandi et al. 2017a), have been proposed to explain the increase of red galaxies with stellar mass (mass quenching). The morphology-segregation effect (Dressler 1980), as well as the decrease of the star formation activity of galaxies in dense regions (environmental quenching), have been explained with other mechanism. These can be devided in two main families, those related to the gravitational interactions expected in high density regions (galaxy-galaxy - Merritt (1983); galaxy-cluster - Byrd & Valtonen (1990); harassment - Moore et al. (1998)), and those due to the interaction of the interstellar medium (ISM) of galaxies moving at high velocity ($\sim$ 1000 km s$^{-1}$) within the hot ($10^7$-$10^8$ K) and dense ($\rho_{ICM} \sim 10^{-3}$ cm$^{-3}$; Sarazin (1986)) intracluster medium (ICM) trapped within the potential well of clusters (ram pressure - Gunn & Gott (1972); viscous stripping - Nulsen (1982); thermal evaporation - Cowie & Songaila (1977); starvation - Larson et al. (1980)). All these processes can start to be active well before galaxies enter rich clusters, when they aggregate in small groups that will later infall into the most massive sturctures observed in the local Universe (pre-processing, Dressler (2004); Cortese et al. (2006)).

The identification of the dominant quenching process is crucial to tune cosmological simulations and semi-analytic models of galaxy evolution. This exercise, however, is very difficult, since different quenching mechanisms are expected to dominante in different environments, at different epochs, and on galaxies of different mass.

[1] Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille), UMR 7326, F-13388, Marseille, France

## 2 Environmental quenching

The dominant quenching mechanism in high density regions can be identified by combining the multifrequency analysis of complete samples of galaxies selected according to strict criteria, or the detailed study of representative objects, with the predictions of tuned models and simulations. The statistical analysis of complete samples can be used to derive observationally the typical angular scales and timescales on which the perturbation is active, and compare them to the predictions of models and simulations. Indeed, gravitational perturbations, such as galaxy harassment, are expected to be efficient well within the virial radius of the high density region where the density of galaxies is sufficiently high (e.g. Moore et al. (1998)), and require long timescales (several Gyr) to allow multiple fly-by encounters to occur. Starvation (the gentle consumtion of the cold gas located on the disc of the galaxy via star formation once infall of fresh gas is stopped), on the contrary, starts to be active at several virial radii, when the galaxy becomes for the first time satellite of the cluster halo (Larson et al. 1980). Starvation also requires several Gyr to totally quench the star formation activity of the perturbed galaxies given the large amount of gas available on their discs (Boselli et al. 2006, 2014d,b,c). Models and simulations indicate that ram pressure is much more efficient since it is able to remove most of the gas from the disc in a few hundreds Myr, and totally quench the activity of star formation in $\leq$ 1.5 Gyr (Roediger & Hensler 2005; Tonnesen & Bryan 2009). Furthermore, the observations of peculiar galaxies with extended tails of gas, witnessing an ongoing stripping process, well outside the virial radius suggest that this mechanism start to be efficient even at the periphery of clusters (Chung et al. 2007; Scott et al. 2012).

Other clear imprints of the different mechanisms are the presence of asymmetric low surface brightness tails of gas and stars in gravitational perturbations, combined with an enached nuclear star formation activity, and the presence of truncated stellar discs and bars (e.g. Mastropietro et al. (2005)). An homogeneous fading of the star formation rate along the disc of the perturbed galaxies, with possibly an increase of the contribution of the nuclear feedback, is instead expected in a starvation scenario. Gaseous tails with a cometary shape without any old stellar counterpart, as well as truncated discs in the different components of the ISM (gas - dust) and in the youngest stellar populations are produced by the outside-in stripping of the gas in a ram pressure stripping event.

## 3 The nearby Universe

In the last years we have done a huge effort to identify the dominant perturbing mechanism in nearby clusters of galaxies. This effort has been done both observationaly, collecting data at different frequencies to map the distribution of the different components of the ISM (cold gas: HI, $H_2$; ionised gas: Halpha; hot gas: X-rays; dust: infrared) and of the different stellar populations in representative nearby clusters such as Virgo, Coma, and A1367 (Boselli et al. 2014d; Gavazzi et al. 2010, 2013), and through the developement of tuned models and simulations expressely tailored to take into account the effects of the different perturbing mechanisms typical of rich environments (Boselli et al. 2006, 2008a,b). All results consistently indicate ram-pressure as the dominant mechanism in nearby clusters of mass $10^{14}$-$10^{15}$ $M_{\odot}$. Indeed we have observed that the the stripping of the ISM, which occurs on HI (Gavazzi et al. 2005, 2006, 2013; Boselli et al. 2014d), $H_2$ (Fumagalli et al. 2009; Boselli et al. 2014b; Scott et al. 2015), and dust (Cortese et al. 2010, 2012b), is able to quench the activity of star formation of galaxies up to $\simeq$ the virial radius of the cluster. We have also shown that the stripping of all the difference phases of the ISM is outside-in, producing truncated HI, $H_2$ and dust discs (Fig. 1; Cayatte et al. (1994); Cortese et al. (2010); Boselli et al. (2014b)). As a consequence, the activity of star formation in the perturbed galaxies continues only in the inner disc, while the outer disc is dominated by an old stellar populations (Boselli & Gavazzi 2006; Boselli et al. 2006, 2015; Koopmann et al. 2006; Cortese et al. 2012a; Fossati et al. 2013). There is also clear evidence that a large fraction of late-type galaxies in these and other nearby clusters have extended cometary tails of stripped gas witnessing an ongoing ram pressure stripping event. These tails have been observed in radio continuum (Gavazzi et al. 1995), HI (Chung et al. 2007; Scott et al. 2012), X-rays (Sun et al. 2007), but are becoming more and more evident in very deep H$\alpha$ narrow-band imaging now made possible thanks to large panoramic detectors coupled to 4-8 metre class telescopes (Gavazzi et al. 2001a; Yoshida et al. 2002; Yagi et al. 2007, 2010, 2017; Kenney et al. 2008; Fossati et al. 2012, 2016; Fumagalli et al. 2014; Boselli et al. 2016a). These results are at the origin of the Virgo Environmental Survey Tracing Ionised Gas Emission (VESTIGE; Boselli et al. in prep.), a narrow-band H$\alpha$ imaging survey of the Virgo cluster that we are undertaking at the CFHT.

More recently we have tried to quantify the typical timescale for the quenching of the star formation activity of late-type galaxies in the Virgo cluster (Ciesla et al. 2016; Boselli et al. 2016b). We have done this exercice

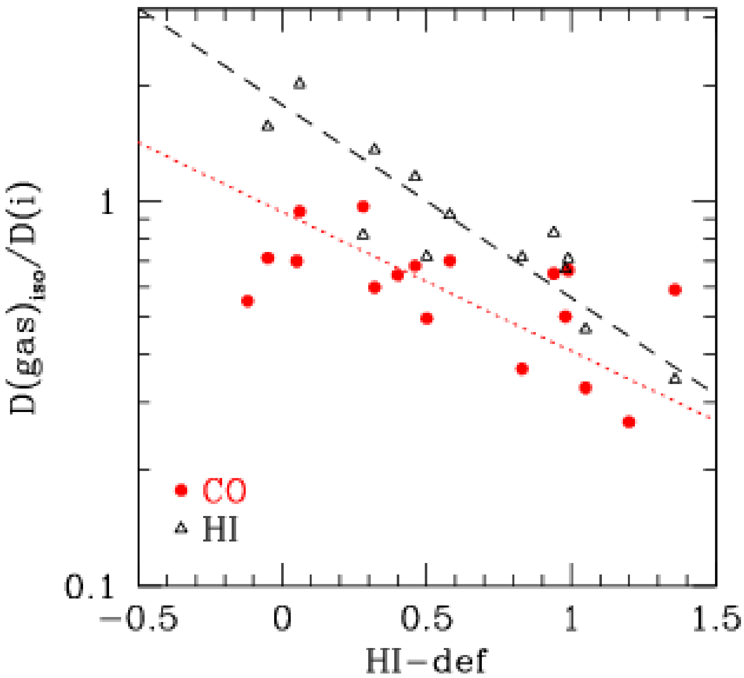


**Fig. 1.** Relationship between the gas-to-stellar ($i$-band) isophotal diameter ratio and the HI-deficiency parameter for galaxies of the Herschel Reference Survey, a stellar mass-selected, volume-limited sample including the Virgo cluster (Boselli et al. 2010). Red filled dots are for CO data, black open triangles for HI data. The red dotted and black dashed lines indicate the best fit to the molecular and atomic gas data, respectively. Adapted from Boselli et al. (2014b)

by fitting the observed UV-to-far infrared spectral energy distribution (SED) of $\sim$ 300 galaxies in the Herschel Reference Survey (HRS; Boselli et al. (2010)) with the CIGALE SED fitting code (Noll et al. 2009). To better constrain the typical quenching timescale we have added to the available 20 photometric bands the integrated spectra of the galaxies (Boselli et al. 2013) which includes several age-sensitive absorption lines from the Balmer series, and the narrow-band H$\alpha$ imaging sensitive to the youngest stellar populations ($< 10^7$ yr; Boselli et al. (2009)). To reproduce the quenching episode we have used truncated star formation histories characterised by a secular evolution (indicised on the velocity rotation of the galaxy, available from HI spectra, Boselli et al. (2014a)), where the only free parameters are the epoch of the quenching and the quenching factor. This star formation history well matches the observed SED of perturbed galaxies (Boselli et al. 2016b). The analysis of this sample indicated that in most of the HI-deficient galaxies of the Virgo cluster the activity of star formation has been quenched only recently, $\leq$ 250 Myr, as depicted in Fig. 2, and thus that the quenching episod has been rapid, as expected in a ram pressure stripping scenario (Boselli et al. 2016b).

Although ram pressure seems the dominant mechanism perturbing galaxies in these nearby clusters, there are also examples of objects undergoing other kinds of perturbations. A clear example is the galaxy NGC 4438 in Virgo, where the presence of extended tidal tails in the stellar component are a clear sign of a gravitational perturbation (Combes et al. 1988; Boselli et al. 2005; Vollmer et al. 2005). In other objects gravitational perturbations can contribute to make ram pressure stripping more efficient such as in the three galaxies CGCG 97-73, 97-79, and 97-87 in A1367 (Gavazzi et al. 2001a,b; Consolandi et al. 2017b), or in NGC 4654 in Virgo (Vollmer 2003). Among these the most spectacular case is certainly the Blue Infalling Group in A1367 (BIG) first discovered by Sakai et al. (2002) and Gavazzi et al. (2003) and then studied in detail by Cortese et al. (2006). Indeed, this is the best example of pre-processing in a nearby cluster.

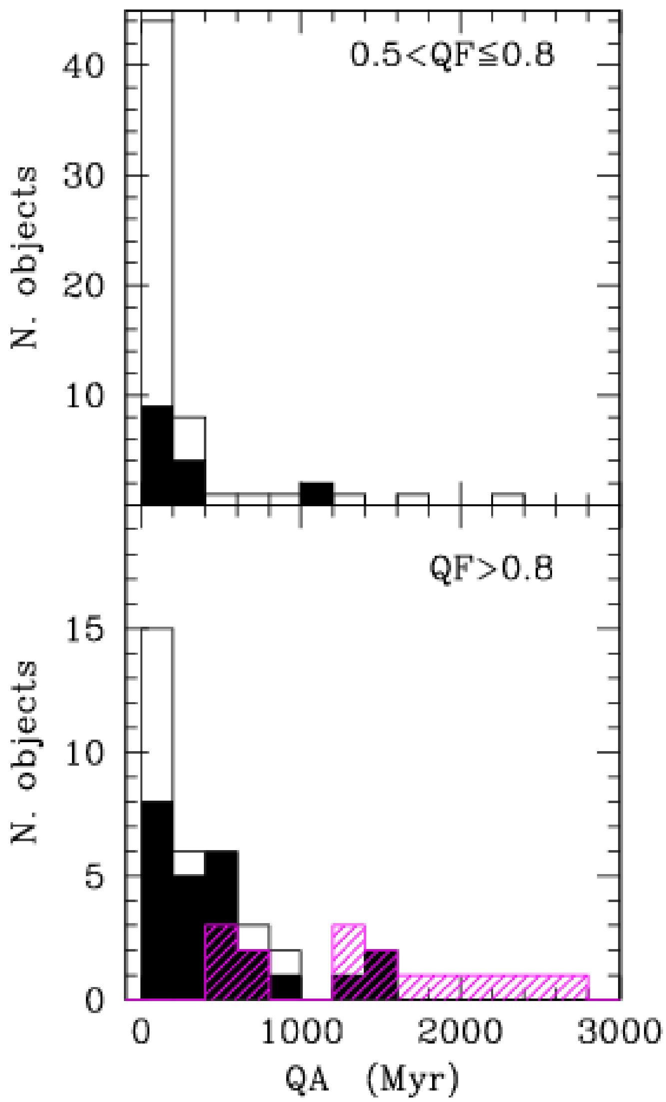


**Fig. 2.** Distribution of the quenching age parameter (QA) with a quenching factor 0.5<QF<0.8 upper panel) and QF>0.8 (lower panel). The magenta histogram is for early-type galaxies, the empty histogram for all late-type galaxies, and the black shaded histogram for HI-deficient late-type systems. Adapted from Boselli et al. (2016b)

## 4 Conclusions

The multifrequency analysis of late-type galaxies in the nearby clusters Virgo, Coma, and A1367, the detailed study of representative objects, and the results of models and simulations tailored to reproduce the observed properties of representative objects consistently indicate ram pressure stripping as the dominant mechanism modulating the star formation history in rich environments. These results, however, are in apparent disagreement with those found by the analysis of other larger samples of local or high-$z$ galaxies with optical data which rather suggest a gentle decrease of the star formation activity over $\sim$ 5 Gyr followed by a rapid decrease in the last 0.5 Gyr (pre-processing; e.g. Wetzel et al. (2012, 2013); Fossati et al. (2017)), or a slow decrease of the star formation activity (starvation: e.g. McGee et al. (2009); Haines et al. (2015)). They also disagree with the prediction of semi-analytic models of galaxy evolutions or cosmological simulations, which generally overpredict the number of quiescent galaxies with respect to observations (e.g. Hirschmann et al. (2014)). An important effort by observers and modelers is still necessary if we want to fully understand the role of the environment on galaxy evolution.

I would like to thanks all my collaborators with whom I had the pleasure to work during these years. This work has been partly supported by the French national program PNCG

## References

Boissier, S., Boselli, A., Prantzos, N., & Gavazzi, G. 2001, MNRAS, 321, 733
Boissier, S. & Prantzos, N. 2000, MNRAS, 312, 398
Boselli, A., Boissier, S., Cortese, L., et al. 2009, ApJ, 706, 1527
Boselli, A., Boissier, S., Cortese, L., & Gavazzi, G. 2008a, ApJ, 674, 742
Boselli, A., Boissier, S., Cortese, L., & Gavazzi, G. 2008b, A&A, 489, 1015
Boselli, A., Boissier, S., Cortese, L., et al. 2005, ApJ, 623, L13
Boselli, A., Boissier, S., Cortese, L., et al. 2006, ApJ, 651, 811
Boselli, A., Cortese, L., & Boquien, M. 2014a, A&A, 564, A65
Boselli, A., Cortese, L., Boquien, M., et al. 2014b, A&A, 564, A67
Boselli, A., Cortese, L., Boquien, M., et al. 2014c, A&A, 564, A66
Boselli, A., Cuillandre, J. C., Fossati, M., et al. 2016a, A&A, 587, A68
Boselli, A., Eales, S., Cortese, L., et al. 2010, PASP, 122, 261
Boselli, A., Fossati, M., Gavazzi, G., et al. 2015, A&A, 579, A102
Boselli, A. & Gavazzi, G. 2006, PASP, 118, 517
Boselli, A. & Gavazzi, G. 2014, A&A Rev., 22, 74
Boselli, A., Gavazzi, G., Donas, J., & Scodeggio, M. 2001, AJ, 121, 753
Boselli, A., Hughes, T. M., Cortese, L., Gavazzi, G., & Buat, V. 2013, A&A, 550, A114
Boselli, A., Roehlly, Y., Fossati, M., et al. 2016b, A&A, 596, A11
Boselli, A., Voyer, E., Boissier, S., et al. 2014d, A&A, 570, A69
Byrd, G. & Valtonen, M. 1990, ApJ, 350, 89
Cayatte, V., Kotanyi, C., Balkowski, C., & van Gorkom, J. H. 1994, AJ, 107, 1003
Chung, A., van Gorkom, J. H., Kenney, J. D. P., & Vollmer, B. 2007, ApJ, 659, L115
Ciesla, L., Boselli, A., Elbaz, D., et al. 2016, A&A, 585, A43
Combes, F., Dupraz, C., Casoli, F., & Pagani, L. 1988, A&A, 203, L9
Consolandi, G., Dotti, M., Boselli, A., Gavazzi, G., & Gargiulo, F. 2017a, A&A, 598, A114
Consolandi, G., Gavazzi, G., Fossati, M., et al. 2017b, ArXiv e-prints
Cortese, L., Boissier, S., Boselli, A., et al. 2012a, A&A, 544, A101
Cortese, L., Ciesla, L., Boselli, A., et al. 2012b, A&A, 540, A52
Cortese, L., Davies, J. I., Pohlen, M., et al. 2010, A&A, 518, L49
Cortese, L., Gavazzi, G., Boselli, A., et al. 2006, A&A, 453, 847
Cowie, L. L. & Songaila, A. 1977, Nature, 266, 501
Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ, 112, 839
Dressler, A. 1980, ApJ, 236, 351
Dressler, A. 2004, Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 206
Fossati, M., Fumagalli, M., Boselli, A., et al. 2016, MNRAS, 455, 2028
Fossati, M., Gavazzi, G., Boselli, A., & Fumagalli, M. 2012, A&A, 544, A128
Fossati, M., Gavazzi, G., Savorgnan, G., et al. 2013, A&A, 553, A91
Fossati, M., Wilman, D. J., Mendel, J. T., et al. 2017, ApJ, 835, 153
Fumagalli, M., Fossati, M., Hau, G. K. T., et al. 2014, MNRAS, 445, 4335
Fumagalli, M., Krumholz, M. R., Prochaska, J. X., Gavazzi, G., & Boselli, A. 2009, ApJ, 697, 1811

Gavazzi, G., Boselli, A., Mayer, L., et al. 2001a, ApJ, 563, L23
Gavazzi, G., Boselli, A., van Driel, W., & O'Neil, K. 2005, A&A, 429, 439
Gavazzi, G., Consolandi, G., Dotti, M., et al. 2015, A&A, 580, A116
Gavazzi, G., Contursi, A., Carrasco, L., et al. 1995, A&A, 304, 325
Gavazzi, G., Cortese, L., Boselli, A., et al. 2003, ApJ, 597, 210
Gavazzi, G., Fumagalli, M., Cucciati, O., & Boselli, A. 2010, A&A, 517, A73
Gavazzi, G., Fumagalli, M., Fossati, M., et al. 2013, A&A, 553, A89
Gavazzi, G., Marcelin, M., Boselli, A., et al. 2001b, A&A, 377, 745
Gavazzi, G., O'Neil, K., Boselli, A., & van Driel, W. 2006, A&A, 449, 929
Gavazzi, G., Pierini, D., & Boselli, A. 1996, A&A, 312, 397
Gunn, J. E. & Gott, III, J. R. 1972, ApJ, 176, 1
Haines, C. P., Pereira, M. J., Smith, G. P., et al. 2015, ApJ, 806, 101
Hirschmann, M., De Lucia, G., Wilman, D., et al. 2014, MNRAS, 444, 2938
Kauffmann, G., Heckman, T. M., Tremonti, C., et al. 2003, MNRAS, 346, 1055
Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Kenney, J. D. P., Tal, T., Crowl, H. H., Feldmeier, J., & Jacoby, G. H. 2008, ApJ, 687, L69
Koopmann, R. A., Haynes, M. P., & Catinella, B. 2006, AJ, 131, 716
Larson, R. B., Tinsley, B. M., & Caldwell, C. N. 1980, ApJ, 237, 692
Mastropietro, C., Moore, B., Mayer, L., et al. 2005, MNRAS, 364, 607
McGee, S. L., Balogh, M. L., Bower, R. G., Font, A. S., & McCarthy, I. G. 2009, MNRAS, 400, 937
Merritt, D. 1983, ApJ, 264, 24
Moore, B., Lake, G., & Katz, N. 1998, ApJ, 495, 139
Noll, S., Burgarella, D., Giovannoli, E., et al. 2009, A&A, 507, 1793
Nulsen, P. E. J. 1982, MNRAS, 198, 1007
Peng, Y.-j., Lilly, S. J., Kovač, K., et al. 2010, ApJ, 721, 193
Roediger, E. & Hensler, G. 2005, A&A, 433, 875
Sakai, S., Kennicutt, Jr., R. C., van der Hulst, J. M., & Moss, C. 2002, ApJ, 578, 842
Sarazin, C. L. 1986, Reviews of Modern Physics, 58, 1
Scott, T. C., Cortese, L., Brinks, E., et al. 2012, MNRAS, 419, L19
Scott, T. C., Usero, A., Brinks, E., et al. 2015, MNRAS, 453, 328
Sun, M., Donahue, M., & Voit, G. M. 2007, ApJ, 671, 190
Tonnesen, S. & Bryan, G. L. 2009, ApJ, 694, 789
Vollmer, B. 2003, A&A, 398, 525
Vollmer, B., Braine, J., Combes, F., & Sofue, Y. 2005, A&A, 441, 473
Wetzel, A. R., Tinker, J. L., & Conroy, C. 2012, MNRAS, 424, 232
Wetzel, A. R., Tinker, J. L., Conroy, C., & van den Bosch, F. C. 2013, MNRAS, 432, 336
Yagi, M., Komiyama, Y., Yoshida, M., et al. 2007, ApJ, 660, 1209
Yagi, M., Yoshida, M., Gavazzi, G., et al. 2017, ApJ, 839, 65
Yagi, M., Yoshida, M., Komiyama, Y., et al. 2010, AJ, 140, 1814
Yoshida, M., Yagi, M., Okamura, S., et al. 2002, ApJ, 567, 118