Session 4:

ATOMIC AND MOLECULAR GAS IN GALAXIES:

Cooling Flows, Radio Galaxies,
High-redshift Galaxies,
Epoch of Reionisation

Brightest Cluster Galaxies & Cooling Flows

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Abstract. In the absence of any form of feedback heating, the gas in the central regions of massive relaxed cluster should cool and initiate a cooling flow. The presence/efficiency of an additional heating and the ultimate fate of the cooling gas is the subject of an extensive debate. In the last decade, molecular and atomic gas have been found in many Brightest Cluster Galaxies. I will review these observational results and discuss their implication for galaxy formation/evolution, in the perspective of ALMA.

Keywords. galaxies: cooling flows — intergalactic medium — galaxies: elliptical and lenticular, cD

1. The Brightest Cluster Galaxies and the Intra-cluster Medium

Brightest Cluster galaxies (BCGs) are giant elliptical galaxies standing in the centre of galaxy cluster potential wells. Most of the mass of galaxy clusters lies in the Intra-cluster Medium (ICM), a very hot plasma that emits in the X-ray. A large fraction of galaxy clusters contains a cooling flow (Fabian *et al.*, 1994). BCGs are thus interesting nearby sources to study intergalactic gas cooling/accretion onto galaxies; they are also good laboratories to study the effect of AGN-feedback that may prevent the hot gas from cooling and eventually form stars; two important mechanisms of galaxy formation.

Cool Core Clusters in the X-ray. Cool core clusters (also called cooling flows) are found in about 50-66% of the galaxy clusters identified in the X-ray. The last generation of X-ray satellites, Chandra and XMM-Newton, with respectively a higher spatial and spectral resolution, showed that inside the central 200 kpc, the hot gas has enough time to cool; the hot gas cooling time being as short as a few 100 Myr in the central 50 kpc (Allen et Fabian, 2001; Voigt *et al.* 2003). However the strengths of cooling flows, measured by the so-called X-ray mass deposition rates, were corrected by about one order of magnitude when compared to the numbers derived from ROSAT and the previous generation of X-ray satellites (Peterson *et al.*, 2001), leading to $dM_X/dt \sim$ 10-100 $M_\odot$/yr.

AGN-feedback to regulate cooling flows. A large amount of work has been done in the last decade to study the different feedback processes that could prevent the hot gas from cooling and reduce the mass deposition rates (conduction, SN-feedback, AGN-feedback...). Comparisons of high resolution X-ray images of cluster centres with the radio-emission of the central AGN showed the existence of large X-ray cavities (also called bubbles) that are filled by the radio-jet emission ejected from the central engine. This was the first clear evidence of an interaction between the AGN and the ICM in favor of an energetic feedback coming from the AGN (see Fabian *et al.*, 2012 for a review).

2. Molecular and atomic gas in cooling flows

Before the last decade, BGCs were not considered as possible reservoir of molecular gas. Many attempts had be performed with single dish telescopes and interferometers,
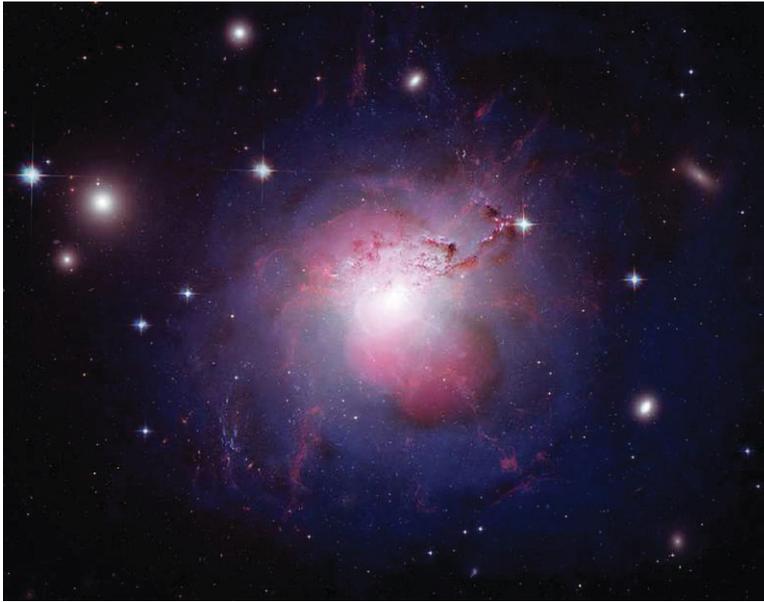
Figure 1. Radio-lobes at 328 MHz in pink. X-ray emission [0.3-7 keV] in violet: diffuse ICM emission and shells around the lobes. Optical data in red, green and blue (stars, filaments, background galaxies, dust-lane; see the on-line proceedings for a color version of this figure). Credit: NASA CXC/IoA/A.Fabian *et al.*; NRAO/VLA/G. Taylor; NASA/ESA/Hubble Heritage (STScI/AURA) & Univ. of Cambridge/IoA/A. Fabian.

to detect a cold gas reservoir built up from the ICM cooling (Grabelski et Ulmer, 1990, McNamara *et al.* 1994, O′Dea *et al.*, 1994, Braine et Dupraz 1994). But no trace of any molecular gas emission was found apart in NGC 1275 that was the only source detected in CO emission lines (Lazareff *et al.*, 1989; Mirabel, 1989; Reuter *et al.*, 1993; Braine *et al.*, 1995; Inoue *et al.*, 1996; Bridges *et al.*, 1998). But it was suspected to be a merger. *Cold gas in a hot environment: the first CO detections* Molecular gas has now been detected mostly via CO(1-0) and CO(2-1) in about 30 BCGs (Edge *et al.*, 2001; Salomé & Combes, 2003) with the IRAM 30m-telescope and the JCMT. The mass of molecular gas in these galaxies is $\sim 10^{8-11.5} M_{\odot}$. So large amounts of gas exist in these giant elliptical galaxies and represent about 10% of what is expected if it was cooling from the hot ICM at rates derived from the X-ray observations. These surveys also showed that the amount of molecular gas correlates with the X-ray mass deposition rates and with the H_{α} luminosities (most of systems with $L(H_{\alpha}) > 10^{41}$ erg s^{-1} being also detected in CO emission lines). No clear anticorrelation was found with the AGN radio emission.

Other molecules and atomic lines. Dense gas or shocked gas tracers (i.e. CN, HCN, HCO+, SiO), were observed but are below the detection limit of current mm-facilities. Only NGC 1275 was detected in HCN(3-2) by Salomé *et al.*, (2008), CN(2-1), C_2H(3-2) and HCO+(3-2) by Bayet *et al.*, (2011). Comparisons with Photodissociation Region (PDR), X-ray Dominated region (XDR), Cosmic-Rays dominated Regions (CRDR) modeling start to be possible (Bayet *et al.*, 2010) and ALMA will open a new era for understanding the physical conditions of the molecular gas in BCGs. *Herschel* detected FIR atomic lines (CII, OI, NII) and continuum dust emission. The derived line diagnostics are like typical star forming galaxies (Edge *et al.*, 2010a,b). Large scale mapping of Perseus and Centaurus were even possible and showed different line excitation conditions for those two objects (Mittal *et al.*, 2011, 2012). In the case of Centaurus, in order to explain the

atomic and optical spectra, another source of heating than the one provided by PDR and HII regions is required (i.e. cosmic rays, shocks or reconnection diffusion).

Evidence of a multiphase ICM and star formation in BCGs In the last decade, tracers of gas at different temperatures were also detected: in the X-ray (Fabian 1994), the UV via the OVI line (Bregman *et al.*, 2001), the optical via the H$_\alpha$ emission (Heckman *et al.*, 1989, Crawford *et al.*, 1999, Mc Donalds *et al.*, 2011 and references therein), the near-IR and mid-IR, via the ro-vibrational (Donahue *et al.*, 2000, Edge *et al.*, 2002) and the pure rotational H$_2$ lines (Egami, 2006, Johnstone *et al.*, 2007, Donahue *et al.*, 2011). BCGs are also places of star formation. Star formation rates estimated from the the mid-IR (O'Dea *et al.*, 2008), the FUV (O'Dea *et al.*, 2010) and the FIR (Edge *et al.*, 2010) are consistent and of the order of 1-50 M$_\odot$/yr, typical of local star forming galaxies and about one order below the X-ray mass deposition rates. The molecular gas found in BCGs is thus a reservoir of material available to fuel the star formation. But what triggers the star formation in BCGs is still an open question.

3. Where is the cold gas?

Single dish telescopes and current mm-submm receivers have shown the presence of large amount of molecular gas in BCGs. Interferometers then looked at the spatial distribution and kinematics of the CO emission in the strongest systems, aiming at finding a possible signature of a cooling flow origin. Edge et Frayer (2003) showed with OVRO that most of the emission seems to be concentrated within the central <20 kpc around the central galaxy in Abell 1068, Zw3146, RXJ0821+07, A1835, RXJ 0338+09. Observations of NGC 1275 seem however to show that the emission could be more extended ~ 50 kpc (Salomé *et al.*, 2011). At the distance of NGC 1275, 1″ is 370 pc, so this BCG is not only the strongest CO emitter of its kind, but it also a perfect target for sensitive and relatively high spatial resolution observations both at small scales around the AGN at very large distances from the centre.

At small scales: evidence for AGN fueling Observations of the central 40″ (14 kpc) of NGC 1275, with the Heterodyne Receiver Array (HERA) on the IRAM 30m-telescope, showed that the CO(2-1) emission was extended along the East-West axis, following the Hα emission (Salomé *et al.*, 2006). A velocity map of this region showed no sign of rotation, but positive velocities on both sides of the centre and negative velocities close to the AGN. This can be the sign of infalling or outflowing gas. Lim *et al.* (2008) and Ho *et al.*, (2009) confirmed this trend with the Submillimeter Array (SMA) and proposed a model of free falling gas to explain the velocity field inside the same region. Recent single dish observations (Salomé *et al.*, 2011) pointed out a double horn profile in the central 11″ (4 kpc). Even closer to the AGN, Wilman *et al.*, (2005) showed evidence of rotation inside the 1″ (370 pc), with long slit observations of the H$_2$ ro-vibrational line. All those observations point towards multiscale evidences of gas accretion onto the AGN. In Abell 1795, the only other source where the CO is resolved in kinematically separated components, Salomé *et al.*, (2004) reported a molecular gas velocity gradient ($\sim$300 km/s over $\sim$6 kpc) that can also be explained by gas accretion onto the AGN. The CO morphology, in this source, follows the one seen in X-ray, optical and UV: (i) along the northern radio-lobe and (ii) around the AGN.

At large scales: a very extended network of molecular filaments NGC 1275, in the centre of the Perseus cluster is famous for its huge filamentary structure seen in the optical (Conselice *et al.*, 2001 and references therein) and in soft X-ray (Fabian *et al.*, 2006). These filaments were detected in H$_2$ by Hatch *et al.* (2005). The IRAM-30m telescope and the Plateau de Bure interferometer showed that these filaments are made of
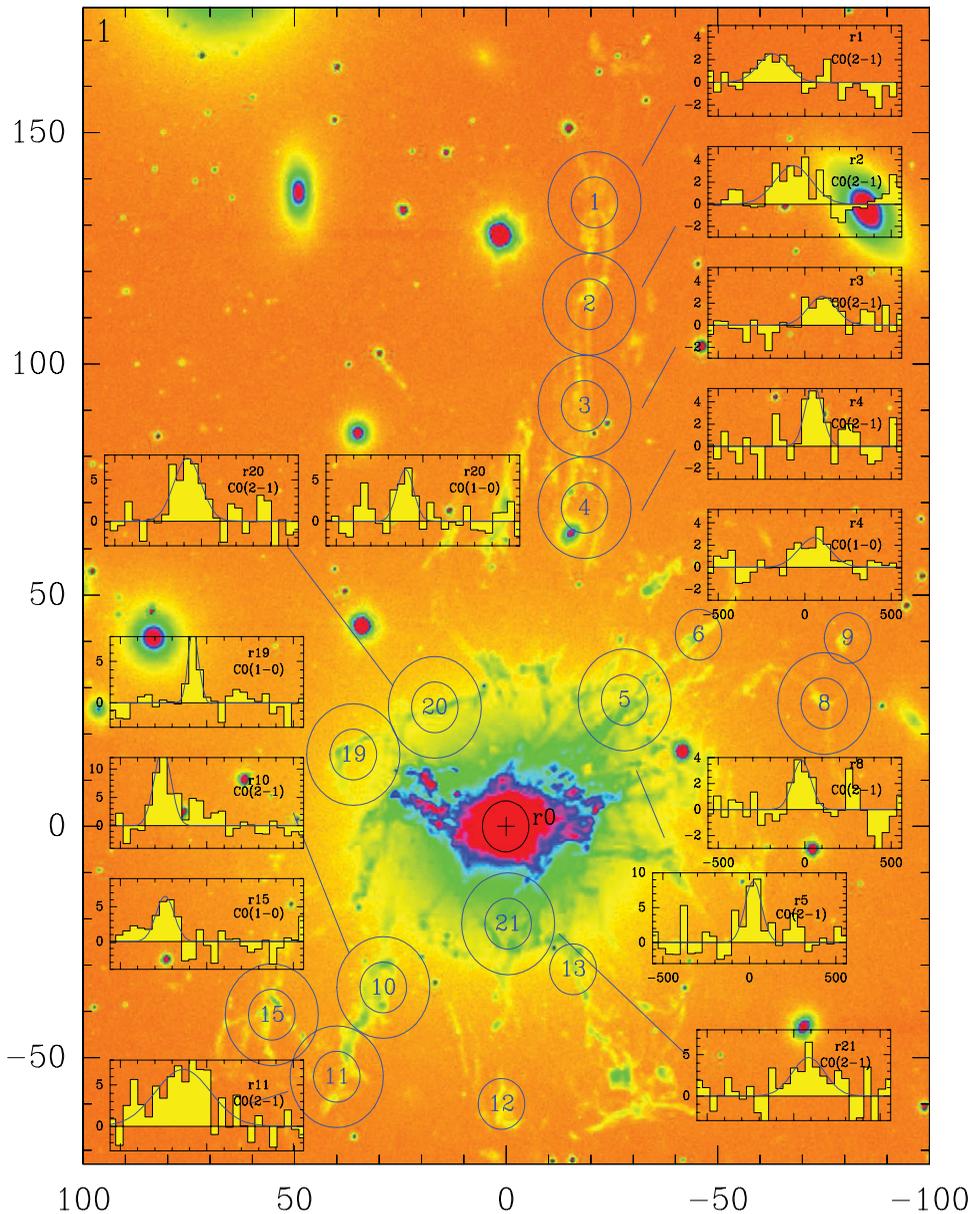
Figure 2. CO spectra superposed on the Hα filament structure around NGC 1275 (Conselice *et al.*, 2001). The double circles show the 1.3 and 3 mm beamwidths at the regions where CO was detected. CO(1–0) and CO(2–1) spectra are shown when detected. The channel width is 42 km/s and the y-axis is main beam brightness temperature, in mK. The velocity scale is from −560 to 560 km/s in each insert. Small circles (1.3 mm beamwidth) show regions where no CO was detected. The image size is 200″×250″ ie 74 kpc×92.5 kpc (Salomé *et al.*, 2011).

molecular gas, with the bulk of the mass lying in the form of very cold gas (Salomé *et al.*, 2006; 2008a,b, 2011). The CO(2–1) emission line is detected at distances as far as ∼50 kpc from the central galaxy in a thin and elongated filament, the outermost region containing up to ∼10^7 M$_\odot$ of cold gas. This very distant filament has not only the same morphology, but also the same dynamics in CO and H$_\alpha$, over a distance of ∼35 kpc.

Evidences for AGN-driven cold filaments It is difficult to explain the presence of molecular gas at such large distances from the galaxy. How could molecular gas form in the very hot ICM? Revaz *et al.*, (2008) performed numerical simulations to study the influence of the AGN on the formation of cold filaments. Along the radio-lobes (expanding in the ICM), where the hot gas is compressed, the over-dense regions can cool more efficiently. The simulations showed that buoyantly rising cavities in the ICM can drag out this cooling gas. When the gas is very cold, it can decouple from the outflowing gas and fall back onto the central galaxy from regions as far as $\sim$50 kpc, as observed in CO.

4. What is the main source of excitation?

Optical line ratios in BCGs are typical of Low Ionization Nuclear Emission Regions (LINER), (ie Heckman *et al.*, 1989; Crawford *et al.*, 1999). This is true even at large distance from the AGN (McDonald *et al.*, 2011). Recently, Lim *et al.*, (2012) mapped the H_2 1-0 in NGC 1275 and found a H_2/H_α ratio of $\sim$-0.08 over the whole nebula. This ratio does not change with the distance from the AGN. So a direct influence of the AGN on the filaments excitation seems to be ruled out. The question of the main source of excitation is still open. The two mechanisms most widely studied are: (i) shocks (Ogle *et al.*, 2010, Nesvadba *et al.*, 2011, Guillard *et al.*, 2012) and (ii) energetic particles (Ferland *et al.*, 2008, 2009).

Molecular hydrogen Pure rotational H_2 S(3) 9.67μm, S(2) 12.28μm, and S(1) 17.04μm lines were detected in BCGs by Spitzer (Egami *et al.*, 2006). Those lines were then found in 9 other BCGs (Donahue *et al.*, 2011): 2A0335, A478, A1068, A1795, A1835, A2597, HydraA, MS0735, PKS0745. Johnstone *et al.*, (2007) also detected them in several filaments in NGC 1275. The H_2 lines very are bright and the H_2/PAH ratio is high ($\leqslant$0.03). So BCGs look like the MOHEGs (Molecular Hydrogen Emitting Galaxies) found by the Spitzer satellite. PDR models alone cannot explain such high line ratios (Guillard *et al.*, 2012). Another source of energy is required to power the hydrogen emission lines.

Cosmic Rays vs Kinetic energy dissipation Around radio-galaxies, Guillard *et al.*, (2012) argues for AGN-winds energy dissipation by shocks. In BCG filaments, large scale kinetic energy dissipation is a possible mechanism that needs to be studied. The extra-energy required by the observations could also be provided by energetic particles (secondary electrons) collisional heating and ionization (Ferland *et al.*, 2008, 2009). But this needs very high cosmic ray ionization rates. More recently, Fabian *et al.*, (2011) proposed that this heating/ionization could be due to the hot surrounding gas penetrating the cold gas (hot/cold gas mixing) via magnetic reconnection.

5. Cooling flows in the ALMA era

The current mm-facilities have shown the existence of large amount of gas in BCGs. The emission is however very faint and few objects have been mapped. When resolved, the cold gas lies in extended filaments also visible in the optical and soft X-ray. Now is the time of ALMA, that will revolutionize our understanding of cooling flows.

More CO transitions, other molecules, dust The ALMA sensitivity and its sub-millimeter bands will open the access to high-J CO lines and new molecules, like observed in nearby star forming/radio-galaxies. ALMA will determine the dominant excitation mechanism in cooling flows and help understand the nature of the molecular gas around BCGs. It will also map in great details the dust pointed out by *Herschel* very recently.

Details of the central region The ALMA high spatial resolution and sensitivity will give access to the very central region, around the AGN. It will look for signs of accretion

disks and molecular outflows and study the details of the AGN-fueling/feedback in BCGs.

Increase the sample, look for filaments ALMA will determine whether all BCGs are surrounded by large molecular filaments. It is a key step to understand the gas accretion mechanisms on galaxies and the possible influence of the AGN (that could enhanced local cooling and lead to the formation of cold/cooling filaments).

References

Allen S., Schmidt, R., & et Fabian, A. C. 2001, *MNRAS* 328, 37
Bayet, E., Hartquist, T. W., Viti, S., Williams, D. A., & Bell, T. A., 2010, *A&A*, 521, 16
Bayet, E., Hartquist, T. W., Viti, S., Williams, D. A., & Bell, T. A. 2011, *MNRAS* 414, 1583
Braine J. & Dupraz C. 1994, *A&A* 283, 407
Braine J., Wyrowski, F., Radford, S. J. E., Henkel, C., & Lesch, H 1995, *A&A* 293, 315
Bregman, Joel N., Miller, Eric D., Irwin, & Jimmy A., 2001, *ApJ* 553, 125
Bridges T. J. & Irwin J. A. 1998, *MNRAS*, 300, 967
Conselice, C. J., Gallagher, J. S., & Wise, R. F. G. 2001, *AJ*, 122, 2281
Crawford C. S., Allen S. W., Ebeling H., Edge A. C, & Fabian A. C. 1999 *MNRAS*, 306, 857
Donahue, Megan, de Messires, Genevive E., O'Connell, *et al.*, 2011, *ApJ*, 732, 40
Edge A. C. 2001, *MNRAS*, 328, 762
Egami, E., Rieke, G. H., Fadda, D., & Hines, D. C., 2006, *ApJ*, 652, 21
Fabian A. C. 1994, *ARAA* 32, 277
Fabian A. C. Sanders, J. S., Williams, R. J. R., Lazarian *et al.* 2011, *MNRAS* 418, 2154
Fabian A. C. 2012, *ARAA* 50, 455
Fabian, A. C., Sanders, J. S., Taylor, G. B. *et al.*, 2006, *MNRAS*, 366, 417
Ferland, G. J., Fabian, A. C., Hatch, N. A., Johnstone, R. M. *et al.*, & *MNRAS*, 2008, 386, 72
Ferland G., Fabian, A. C. Hatch, N. A., *et al.* 2009, *MNRAS*, 392, 1475
Grabelski, D. & Ulmer, M 1990, *ApJ*, 355, 401
Guillard, P., Ogle, P. M., Emonts, B. H. C., Appleton, *et al.*, 2012, , *ApJ* 747, 95
Hatch, N. A., Crawford, C. S., Fabian, A. C., & Johnstone, R. M. J., 2005, *MNRAS*, 358, 765
Heckman, T. M., Baum, S. A., van Breugel, W. J. M., & McCarthy, P., 1989, *ApJ*, 338, 48
Ho, I.-Ting, Lim, Jeremy, & Dinh-V-Trung 2009, *ApJ*, 698, 1191
Inoue, M. Y., Kameno, S., Kawabe, R., Inoue, M., Hasegawa, T., & Tanaka, M. 1996, *AJ*, 111
Johnstone, R. M., Hatch, N. A., Ferland, G. J., Fabian, A. C. *et al.*, 2007, *MNRAS*, 382, 1246
Lazareff B., Castets A., Kim D. W., & Jura M. 1989, *ApJ* 335, L13
Lim, J., Ao, Y., & Trun, D-V. 2008, *ApJ*, 672, 252
Lim, Jeremy, Ohyama, Youichi, Chi-Hung, Yan, *et al.* 2012, *ApJ*, 744, 112
McDonald, Michael; Veilleux, Sylvain; & Mushotzky, Richard, 2011, *ApJ*, 731, 33
McNamara B. R., & Jaffe W. 1994, *A&A*, 281, 673
Mirabel, I. F., Sanders, D. B., & Kazes, I., 1989, *ApJ*, 340, 9
Nesvadba, N. P. H., Boulanger, F., Lehnert, M. D., Guillard, P., & Salome, P., *A&A*, 2011, 536, 5
O'Dea C. P., Baum S. A., Maloney P. M., *et al.*, 1994, *ApJ*, 422, 467
Ogle, Patrick, Boulanger, Francois, Guillard, Pierre, *et al.*, 2010, *ApJ*, 724, 1193
Peterson J. R., Paerels F. B. S., Kaastra J. S., Arnaud M., *et al.*, 2001, *A&A* 365, L104
Reuter, H. P., Pohl, M., Lesch, H., & Sievers, A. W. 1993, *A&A*, 277
Revaz Y., Combes F., & Salomé P. 2008, *A&A*, 477, 33
Salomé, P., & Combes, F., 2003, *A&A*, 412, 657
Salomé, P., Combes, F., Edge, A. C., *et al.* 2006, *A&A*, 454, 437
Salomé, P., Combes, F., Revaz, Y, *et al.* 2008a, *A&A*, 484, 317
Salomé, P., Revaz, Y., Combes, F., *et al.* 2008b, *A&A*,483, 793
Salomé, P., Combes, F., Revaz, Y., al 2011, *A&A*, 531, 85
Voigt, L. & Fabian, A. C. 2004, *MNRAS*, 347, 1130
Wilman, R. J., Edge, A. C., & Johnstone, R. M. 2005, *MNRAS*, 359, 75