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A first glimpse into ISM/ICM connections at z=0.2 with ISOCAM*

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Abstract. Although it is well established that the cluster environment affects the gas content and massive star formation in galaxies, the mechanisms have not yet been unambiguously identified. In order to elucidate some of the processes responsible, an ISO Core Programme - DEEPXSRC - is dedicated to deep observations of medium redshift rich clusters of galaxies. We present here the first results from this programme, obtained by correlating our ISOCAM observations (at 7.5 and 15 μm) of the cluster A1732 with radio, optical and X-ray images. Some 10 distant IR galaxies are detected in an $8' \times 8'$ field and are the faintest extragalactic sources detected by ISO so far.

Key words: Cosmology: observations (ISO, ROSAT, Australia Telescope) – Galaxies: clusters: individual Abell 1732 – Infrared: galaxies – X-ray: general – Radio continuum: galaxies

1. Introduction

Interactions between cluster galaxies and the intra-cluster medium (ICM) are known to be among the most efficient processes for driving cluster evolution and producing the strong differentiation between cluster and field galaxies.
There are likely to be many factors involved in the ISM–ICM interaction, but these have generally been studied in isolation from one another: galaxy formation and morphology, cluster galaxy population and luminosity functions, tidal interactions and star formation rate, enrichment of the ICM in heavy elements (including radial variations of any of these quantities), fate of the huge amounts of gas accumulating onto the cD in cooling flow clusters, dynamics and motions of the ICM, as well as the dark matter content and distribution which has an influence on all scales. While these fundamental aspects have been the subject of numerous observational and theoretical studies in recent years, their detailed inter-connections remain to be identified unambiguously. In order to provide some decisive tests to help disentangle the physical processes occurring, we have constructed a database covering the entire electromagnetic spectrum (Pierre et al 1994a):
(1) *X-ray* information is fundamental for determining cluster temperatures and masses (gas, total) as well as iron abundances, and provides decisive constraints on cluster formation processes through the detection of substructures — deep ROSAT and ASCA pointings.
(2) *Ground-based optical* spectroscopy and photometry yield alternative mass estimates and local dynamical information which can be related to the X-ray substructures — observations at CFHT and ESO NTT.
(3) *Radio* structures, in addition to tracing the presence of enhanced nuclear activity in cluster members, provide useful information on the transverse motions of individual galaxies through radio-jet–ICM interactions — radio survey at $\lambda = 35$ cm with the Molonglo Observatory Synthesis Telescope and at 6, 13 and 21 cm with the Australia Telescope Compact Array.
(4) *Infrared* observations obtained with ISO (Kessler et al 1996) are ideal tracers of star-formation processes and will enable us to directly identify some of the specific aspects of the *interplay* between the ISM and ICM listed above. Moreover, the high ISO sensitivity will enable us

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for the first time to flag the presence of all cluster AGNs and star-forming galaxies and investigate in detail how IR and radio activity correlate on cluster scales.

The cluster sample

We have selected from the ROSAT all-sky survey (Pierre et al 1994b) a set of ∼10 clusters of galaxies, having X-ray luminosities greater than 10^{44} erg s^{-1} cm^{-2} and thus, expected to be massive. This implies a high density for the intra-cluster gas and, most likely, a deep gravitational potential. The redshifts cover the range $z = 0.15$–0.31, which is ideal for mapping the whole cluster extent at high resolution in reasonable exposure times. It will also be possible to tackle questions related to cluster evolution by comparison with lower redshift observations. Throughout the paper we assume $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = \frac{1}{2}$.

2. ISO observations

A total of 29 hours was allocated to this ISO Central Programme (DEEPXSRC).

The immediate goal of the ISOCAM observations (Cesarsky et al 1996) is to provide a statistical sample of IR emitting cluster galaxies in order to further probe the role of the environment as revealed by the data at other wavelengths. The infrared index LW2−LW3 (i.e. [5-8.5]−[12-18] μm) will enable us to discriminate AGNs as well as to assign galaxy types. It will also be relevant for detecting any sign of low/high mass star formation in the centres of strong cooling flow clusters. The areas to be mapped and expected sensitivities were determined as a function of redshift; typically, for $z = 0.3$ clusters, we shall detect sources down to a few 10^{-2} mJy in LW2 (∼ ISOCAM sensitivity limit) and cover a field of $8' \times 8'$. A pixel size of $6''$ was chosen in order to maximize the area covered and the number of clusters to be observed, knowing that up to $z = 0.3$ confusion will not be a problem at this resolution. ISOPHOT scans at 90 μm (C100) are performed as well, to investigate the existence of dust and possible diffuse IR emission on cluster scales (e.g. Wise et al 1993). The first sample cluster was observed in early February 1996 and we present here the ISOCAM results. The characteristics of the observations are given in Table 1. In this configuration, pixels of the resulting images are observed four times in the course of the raster, for a total exposure time of 700 s. After standard pre-processing routines (flat-fielding, de-glitching, background estimation, etc.) sources were detected at the 3 (or 4) σ level for the LW2 (or LW3) band respectively, considering the temporal intensity fluctuations of each pixel. The condition for a "source" to be real is that it has been detected as such in at least two of the four detector pixels involved. Candidate sources were then checked interactively to remove spurious detections, such as those produced by a loss of sensitivity after glitch impacts. The flux of each selected pixel is in turn estimated and neighbouring pixels (if any) co-added to yield final fluxes. Detector flux units were converted into mJy following the ISOCAM manual and corrected for point-source flux loss (factor of 1.2). At the present stage of the reduction, fluxes must still be considered as preliminary (at best 50 % accurate), since many factors, like undersampling effects have not been taken into account. Results are presented in Table 2.

Table 1. Observation summary

TARGET: ACO 1732 $z = 0.193$ $L_X \sim 5\ 10^{44}$ erg/s [0.1–2.4keV] Cooling mass flow rate ∼ 200 M$_\odot$/yr
ISOCAM: raster 5×5, δN = δM = $96''$, pixel = $6''$ $t_{\rm int}$= 5s, $N_{\rm exp}$ = 35, filters: LW2, LW3

The cooling mass flow rate was determined from our 30 ksec ROSAT HRI pointing following classical hypotheses (e.g. Fabian et al 1991).

3. Discussion and conclusions

Fig. 1 summarizes the results from the multi-wavelength campaign on A1732. On the R-band CCD image of the cluster obtained at CFHT, we have overlaid:
– the ROSAT HRI contours (red, linear scale)
– the Australia Telescope radio contours at 20 cm (green, log scale); the spatial resolution of both instruments is $\sim 5''$
– the ISO sources detected in the LW2 band (blue circle, diameter = $6''$)
– the ISO sources detected in the LW3 band (yellow squares)

The CCD field size is $\sim 8' \times 8'$. At the cluster redshift, $4'$ represents ∼ 1 Mpc.

There are 27 sources detected in LW2, but only 9 in LW3 for which the background is significantly higher with larger fluctuations. All sources are associated either with an optical counterpart or with an X-ray/radio pointlike source. All 20cm radio sources, but the weakest one, are IR emitters; in particular, radio source number 2 has no obvious optical identification, but has been detected as a bright source both in LW2 and LW3 (dust reddened QSO or radio galaxy?). Sources 2 & 24 are very likely distant background AGNs; however, having no information on their redshifts it is not possible to infer their rest IR spectrum and, consequently, the origin of their very small LW2/LW3 ratio. Source 19 has B and X-ray luminosities compatible with that of an active late-type star at a distance of about 1.25 kpc, possibly in a close binary system; alternatively, it

Table 2. Characteristics of the sources detected by ISOCAM

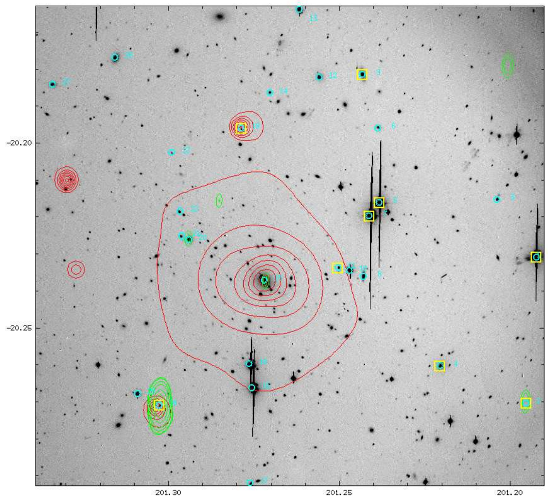
N	RA_{J2000} (*degrees*)	Dec_{J2000} (*degrees*)	LW2 (*mJy*)	LW3 (*mJy*)	B	R	ID	redshift	Radio fluxes (mJy) $35cm, 20cm, 13cm$
1	201.192	-20.231	4.91	0.87	13.7	*	p		
2	201.195	-20.270	0.28	1.80	-	-	-		($\leq$ 2.1), 2.6, 0.8
3	201.203	-20.215	0.24	-	19.9	18.0	p		
4	201.220	-20.260	0.14	0.45	19.5	17.0	g		
5	201.238	-20.216	3.18	0.48	13.3	*	p		
6	201.238	-20.196	0.08	-	20.7	18.9	g?		
7	201.241	-20.219	4.88	0.95	12.9	*	p		
8	201.243	-20.236	0.07	-	20.0	17.7	g	0.187	
9	201.243	-20.181	0.12	0.66	18.9	17.2	g		
10	201.247	-20.234	0.50	-	15.8	*	p		
11	201.250	-20.234	0.06	0.41	19.7	17.9	p?		
12	201.256	-20.182	0.13	-	20.0	17.6	g		
13	201.262	-20.163	0.17	-	15.5	*	p		
14	201.270	-20.186	0.08	-	21.2	19.5	p?		
15	201.272	-20.237	0.39	-	18.6	15.9	cD	0.193	($\leq$ 2.1), 1.3, 1.2
16	201.275	-20.266	2.22	-	13.7	*	p		
17	201.276	-20.292	0.16	-	20.3	18.3	g		
18	201.276	-20.260	1.27	-	13.7	*	p		
19	201.279	-20.196	0.06	0.12	20.5	20.6	p		
20	201.294	-20.226	0.12	-	20.0	17.6	g	0.196	($\leq$ 2.1), 2.1, 0.9
21	201.296	-20.225	0.12	-	21.8	19.3	g	0.192	
22	201.297	-20.218	0.19	-	20.7	18.4	p		
23	201.299	-20.202	0.10	-	22.4	20.6	p?		
24	201.303	-20.271	0.39	2.48	19.7	19.6	p		24.5, 42.6, 50.6
25	201.309	-20.268	0.17	-	16.4	*	p		
26	201.316	-20.176	0.08	-	19.6	17.1	g		
27	201.334	-20.184	0.06	-	20.1	18.2	g		

Optical ID: g stands for galaxy, p for pointlike object in the optical CCD image. Source nb. 20 is a blend of two objects. The B and R photometry was performed on our CFHT CCD images. Blue magnitudes for the * (saturated) stars were obtained from the COSMOS database

could also be some distant active galaxy. About 10 galaxies (including the cD) have been detected in LW2 but only two of them in LW3. Whereas the cD presents the brightest galaxy flux in LW2, we can only set an upper limit of 0.1 mJy on its LW3 flux. This result is fully compatible with the picture of low-mass star formation in a cooling flow galaxy, as massive stars would significantly increase the LW3 contribution. So far we have found no significant correlation between the LW2 flux and optical B and R magnitudes for galaxies.

Four galaxies detected by ISO (see Table 2) had previously been observed in a spectroscopic survey of A1732 at CFHT (Lemonon et al, in preparation). All four spectra have very similar elliptical galaxy characteristics, none of them showing emission lines, and are basically indistiguishable from the cD's at our spectral resolution ($\sim$ 20 Å). The B-R colour of the four galaxies are consistent with that of ellipticals too. Spectra of 2 bright cluster members some $6''$ away from the cD also show no emission lines. As to the ISO colours, the ratio LW2/LW3 is expected to be ~ 1 for spirals where emission from the ISM is dominant (≤ 1, if active star formation), whereas for ellipticals a value $\gg 1$ is expected as most of the IR emission comes from the stellar population (dust in circumstellar envelopes). The fact that none of the confirmed cluster galaxies are detected in LW3 is thus consistent with their being ellipticals (except for the cD, upper limits on LW3 are however compatible with LW2 $\sim$ LW3). The question is then, what makes these particular galaxies bright in IR? A careful look at the CCD images shows that galaxies 15, 8 & 20 have close companions and galaxy 4 (not confirmed as cluster member yet) presents clearly a distorted morphology (other galaxies are probably foreground). A likely answer is thus that we observe IR emission from induced star formation in small gas rich galaxies interacting with the ellipticals; alternatively, this could reflect a post star forming phase in these ellipticals. It is also worthwhile noting that, except for the cD, IR galaxies seem to avoid the cluster central region: the first IR galaxy is found some 350 kpc from the centre, more than twice the X-ray core radius ($\sim$ 140 kpc). This is qualitatively in agreement with

Fig. 1: ISOCAM sources found in the field of the cluster A1732, in combination with data at other wavelengths (see text)



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the classical picture of gas removal of galaxy disk by ram-pressure stripping within the intra-cluster medium and the still open and related question of galaxy morphological segregation. Howerver, it should be noticed that: (i) the high concentration of ellipticals in cluster centers is actually likely to be of innate origin, (ii) gas stripping should be less efficient beyond 3 X-ray core radii (ICM density $\sim 10^{-3}\mathrm{cm}^{-3}$), whereas the optical cluster extents more than three times further ($\sim 5'$). Therefore, the question of the apparent lack of detected spirals remains. The expected LW3 flux for Scd galaxies can be estimated from the low-z correlation ($log[F_B] \propto log[F_{12\mu m}]$) found by Sauvage & Thuan (1994) since the IRAS [8-15]μm band matches approximately the LW3 band at $z \sim 0.2$. Assuming that typical spirals are some 3 magnitude fainter than the cD (B$\sim$ 22) we derive LW3 fluxes of the order of 0.2 mJy, which is somewhat above the detection limit. However, in LW2, we expect for spirals comparable fluxes, which should be well detectable. At such a redshift, evolutionary effects cannot be dominant and a possible explaination is actually that since A1732 is a rich cluster, (richness class I), the fraction of spirals is indeed quite low; based on the cluster X-ray luminosity, we can estimate this fraction to be about 15-20 % (Edge & Stewart 1991); out of these, late-type spirals are certainly even rarer. Undoubtedly, two-color HST images providing detailed galaxy morpholgies are needed in order to follow-up the preliminary answers proposed here.

This first cluster provides a promising outlook for the scientific potential of the programme once the ISO observations are completed. The final cluster sample will yield enough IR galaxies (50–70) for their properties to be characterized statistically across the whole electromagnetic spectrum and associated physical processes to be quantitatively addressed. This preliminary analysis has also shown that, in addition to cluster galaxies, more than 25 IR objects per field can be identified. This should eventually provide an atlas of some 150 faint ISO point sources with optical, radio and X-ray colours.

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