Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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ISOCAM observations of intermediate-redshift galaxy clusters at 7 and 15 μm

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Abstract. The gravitationally lensing clusters A370, A2218, A1689 and Cl0024+1654 were observed with the Infrared Space Observatory (ISO) using ISOCAM at 6.7 μm and 14.3 μm (hereafter 7 μm and 15 μm respectively).

A total of 178 sources were detected in the whole set, 70 of them being cluster objects. The spectral energy distribution of a subset of sources was calculated using GRASIL. The results for the total infrared luminosity and the estimation of the star formation rate are presented for the non stellar objects for which the SED has been determined. The majority of the cluster galaxies in A2218 are best fit by models of quiescent ellipticals. In Cl0024+1654, most of the galaxies lying on the Butcher-Oemler region of the colour-magnitude diagram are best fit by disk galaxies, while those on the main sequence area have in general SEDs corresponding to post-starburst galaxies.

The population of each cluster is compared with the field population, as well as with the population of other clusters. A significant number of Luminous IR Galaxies (LIRGs) is detected in Cl0024+1654, while only one LIRG has been observed in total in A370, A1689, and A2218. This result supports the link between LIRGs in clusters and recent or ongoing cluster merger activity as well as the need for extending the observations to the outer parts of clusters.

1. Introduction

During the science operations of the Infrared Space Observatory (ISO) (Kessler *et al.* 1996), around 180 kiloseconds were devoted by a number of observers to the observation of several galaxy clusters exhibiting strong gravitational lensing (Metcalfe *et al.* 2003, Paper I hereafter, Altieri *et al.* 1999, Barvainis *et al.* 1999, Lémonon *et al.* 1998). These programmes mainly aimed to use lensing amplification to extend the sensitivity of ISOCAM survey measurements. Paper I reported field-source counts extending to the faintest levels achieved with ISOCAM and complementing the field surveys (Elbaz *et al.* 2002).

The observations additionally provided extensive mid-infrared photometry of the clusters themselves. These results have been combined with data at other wavelengths, available in the literature. We have focused on the two well known galaxy clusters: A2218 and Cl0024+1654. The spectral energy distributions of the cluster members are presented, as well as estimations of the stellar formation rate for both clusters.

In Section 2 the data set is described. In Section 3 the main results on A2218 are presented, while those of Cl0024+1654 can be found in Section 4. In Section 5 we compare the spectral energy distributions and stellar formation rates found in the clusters with those of the field galaxies.

We assume $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$. With this cosmology the cluster luminosity distances are 845 Mpc and 2140 Mpc, for A2218 and Cl0024+1654 respectively. At the respective distances of A2218 and Cl0024+1654, 1 arcsecond corresponds to 2.97 kpc and 5.3 kpc and the age of the Universe is 11.3 Gyr and 9.3 Gyr.

2. The data

A2218 and Cl0024+1654 were observed with ISOCAM on board ISO, using the LW2 and LW3 filters (6.7μm and 14.3μm respectively, hereafter 7μm and 15μm). In both cases the observations were carried out in raster mode, to cover a large sky area and to reduce the effects of flat-fielding limitations. In the case of A2218 the rasters were micro-scanned, i.e. the raster step size included a fraction of a pixel distance to achieve better spatial resolution.

The total observing time was 6.2 hours per filter for both clusters, except for the 7μm measurement on Cl0024+1654, which used only a little over 3000 seconds. The total area covered in A2218 was 20.5 arcmin^2 while in Cl0024+1654 areas of 28.6 and 37.8 arcmin^2 were observed at 7μm and 15μm respectively.

For further explanation of the observations and the data reduction refer to Paper I, Biviano *et al.* 2004 (hereafter Paper II), and Coia *et al.* 2004 (hereafter Paper III).

3. Mid-infrared cluster sources in A2218

A2218 is a massive galaxy cluster at $z = 0.175$. Its R_{vir} is 1.63 h^{-1} Mpc and its M_{vir} is $18.27 \times 10^{14} h^{-1} M_\odot$. In total 76 sources were detected in the A2218 field (see Papers I and II).

The velocities and spatial distribution within the cluster of these MIR selected objects do not differ from the rest of the optically selected sources in A2218, so they do not represent a special population from a dynamical point of view.

Photometric data were collected from the literature to calculate spectral energy distributions of the sample. Ten different model SEDs were computed with GRASIL (Silva *et al.*1998) and used to find a best fit model for the observed cluster members. This code calculates the spectral evolution of galaxies by taking into account the effect of dust distributed in the environment as AGB envelopes, diffuse interstellar medium and molecular clouds.

The model SEDs used were distributed as follows: **E:** Three models of early type galaxies with initial bursts of star formation lasting 0.5, 1.0 and 2.0 Gyr. These models were used by Granato *et al.* (2001) and reproduce ellipticals and S0s in the nearby Universe. **S:** Three models of disk galaxies characterized by different values of the gas infall time-scales and the efficiency term in the Schmidt-type law. **SB:** Two starburst models adjusted to fit the moderate starburst galaxy M82 and the strong starburst galaxy Arp220. The starburst is characterized by an e-folding time of 0.05 Gyr and involves ≈ 0.01 and ≈ 0.1 of the total mass of the galaxy respectively. **PSB:** Two post-starburst models corresponding to the previous ones, observed 1 Gyr after the event. All these 10 models were computed at three different ages, forming a final set of 30 possibilities.

The observed and model SEDs were compared using a standard χ^2 procedure, having as free parameters the model SED and the flux normalization. Most of the objects presented SEDs typical of early-type galaxies with none or very small star formation activity. Only four of them presented SFRs above 1 $M_\odot$ yr^{-1} (see Paper II). The remaining sources were best fit by SEDs of passively evolving galaxies. Considering the V−I vs I−K diagram used in Smail *et al.* (2001), the more luminous (and redder) of the cluster members are 5 to 10 Gyr old.

The median infrared luminosity L_{IR} of the cluster sources is $6 \times 10^8 L_\odot$, and none of the objects are significantly blue. This indicates extremely mild star formation activity if any. None of the MIR selected galaxies lies in the Butcher-Oemler region of the V−I vs I diagram.

Several independent analyses based on optical and X-ray observations suggest than A2218 is not a dynamically relaxed cluster. In any case the cluster dynamical status does not appear to affect the MIR properties of its members in the region surveyed.

For further explanation of the data analysis and discussion refer to Paper II.

4. Mid-infrared cluster sources in Cl0024+1654

Cl0024+1654 is a rich cluster of galaxies at $z = 0.395$ with a spectacular system of gravitationally lensed arcs, though, unlike other clusters with these arc-like features, it harbours no central cD galaxy. Its R_{vir} is $0.94\, h^{-1}$ Mpc and its M_{vir} is $6.42 \times 10^{14} h^{-1} M_\odot$. It is one of the two clusters studied by Butcher and Oemler in 1978 and has a significant fraction of blue galaxies ($f_B = 0.16$). As reported by Treu *et al.* (2003), its core is composed of 73% early-type galaxies, with this proportion decreasing to 50% at 1 Mpc and to 43% at its periphery at about 5 Mpc.

Thirteen confirmed cluster sources were detected on the ISOCAM $15\mu m$ map of this field, above the 4σ significance level (Paper III). They all show spatial distributions and velocity characteristics in agreement with the optically selected cluster members. They have special characteristics from the dynamical point of view.

The spectral energy distributions of these sources were obtained following the same strategy as in the A2218 case, though only two different ages of each model were considered. Good fits were obtained for the 12 objects with available optical data. Their total infrared luminosities were calculated based on these SEDs, yielding values ranging from $4.7 \times 10^{10} L_\odot$ to $4.5 \times 10^{11} L_\odot$. Six of these twelve sources have total infrared luminosities above $10^{11} L_\odot$, classifying them as Luminous Infrared Galaxies (LIRGs), and 4 are well within 1σ of this luminosity threshold. 54% are in the Butcher-Oemler region in a colour-magnitude diagram, and these are best fit by spiral galaxy models. On the other hand, the main sequence objects are best fit by post-starburst galaxies (see Paper III).

The results show that all the thirteen cluster objects detected at $15\mu m$ present traces of significant star formation activity. The star formation rate can be derived from the luminosity of the [OII] line, according to the relation SFR[OII] $\approx 1.4 \times 10^{-41}$ L[OII] $M_\odot$ yr^{-1} (Kennicutt 1998), though this method heavily depends on dust extinction, and on the metallicity and ionization of the medium. The SFR can also be obtained from the global infrared luminosity according to the relation $SFR[IR] \approx 1.71 \times 10^{-10} L_\odot$ (Kennicutt 1998). The mean value of the SFR obtained for the cluster members is $30 M_\odot$ yr^{-1}. For three of the sources the SFR has been comparatively calculated through the [OII] flux and through the L_{IR} value. The mean value obtained through the [OII] flux is 10 times lower than that obtained with the L_{IR} value (Paper III). This indicates that the stellar formation activity may be heavily obscured by dust in some or all the observed objects, as also found in A1689 (see Duc *et al.* 2002).

Comparing these results with what has been obtained for other clusters requires a scaling of the LIRG count to allow for different cluster virial radii, masses, distances, and the sky area scanned in each case. For details on this scaling refer to Paper III. In A370

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(a cluster similar to Cl0024+1654 in distance, mass and size) only one cluster object is detected at 15 μm. This sole source is a LIRG, while something like 10 would be expected to have been observed by analogy with the Cl0024+1654 case. The difference may be due to the dynamical characteristics of Cl0024+1654. According to Czoske *et al.* (2002), the cluster is undergoing a major merging event, which may be responsible for the high SFR and L_{IR} observed in some of its galaxies. Yet when comparing with A1689, a cluster similar to Cl0024+1654 in mass and size, but at redshift 0.18, and also having an unrelaxed dynamical status, it is found that the instances of very high SFR in Cl0024+1654 are many more than in A1689, which nonetheless, as mentioned above, shows elevated SFR (Duc *et al.* 2002). In this case, the surveyed portion of the cluster plays a major role, since in the case of A1689 the scanned area belongs to the inner part of the cluster (0.5 Mpc from the centre), while in Cl0024+1654 the area observed has a cluster-centric radius of 2 Mpc, extending to the outer region where the BO galaxies lie.

5. Field galaxies

We have also obtained SEDs of a sample of 14 of the field galaxies detected by ISOCAM in these areas. In general, the field galaxies show stellar formation activity partially or mostly obscured by dust, although this activity is not extremely high in none of them. They are well fitted by models with no significant AGN contribution, being mainly normal spirals and post-starburst galaxies with no major activity events in the last 1 Gyr. 60% of these objects classify as LIRGs, with a median star formation rate calculated from the L_{IR} of 22 $M_{\odot}$ yr^{-1} (Paper II). These values are significantly higher than those obtained in A2218, though comparable to those in Cl0024+1654. The redshift distribution of the field galaxies ranges from 0.1 to 1.1, with a median of $z = 0.6$.

6. Summary and conclusions

We discussed the ISOCAM observations of a number of galaxy clusters, concentrating mainly on the results for A2218 and Cl0024+1654. In the first of these it is found that most of the cluster members detected at 7μm and 15μm have SEDs resembling early-type galaxies with little or no star formation activity. None of them qualify as Butcher-Oemler galaxies and they have a median L_{IR} of $6 \times 10^8 L_{\odot}$, far below the LIRG luminosity threshold. If the cluster has a non-relaxed dynamical status, this does not seem to affect the MIR properties of the cluster galaxies within the area studied.

The cluster Cl0024+1654 harbours 13 sources detected at 15μm, 11 of them are LIRGs having MIR luminosities within 10% of the LIRG threshold of $10^{11} L_{\odot}$, and six fall above that threshold. Six out of the eleven for which I and R band data were available lie in the BO region on a I−R vs I diagram. The SFRs calculated through the L_{IR} values are consistent with disk-like and post-starburst galaxies, and are an order of magnitude higher than the values obtained through the equivalent width of the [OII] spectral line. This may be due to heavy absorption of the UV and visible photons by dust, and their subsequent re-emission in the MIR spectral range.

Comparison with other clusters and with field galaxies suggests a link between the dynamical history of a cluster and star formation in its constituent galaxies. But this link may or may not be observed, depending on which part of the cluster is surveyed. The highest number of LIRGs and the highest SFR are found in the cluster which is undergoing a merging event and the outskirts of which have been included in the observations. It is necessary to extend these studies in number of targets studied and in area covered

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in order to reach firmer conclusions. In this sense, SPITZER can provide excellent data for this purpose.

References

Altieri, B., Metcalfe, L., Kneib, J-P. et al. 1999, A&A 343, 65

Barvainis., R., Antonucci R., Helou, G. 1999, ApJ 118, 645

Biviano, A., Metcalfe, L., McBreen, B. et al. 2004, accepted for publication in A&A, astro-ph/0406391 (Paper II)

Coia, D., McBreen, B., Metcalfe, L. et al. 2004, submitted to A&A (Paper III)

Czoske, O., Moore, B., Kneib, J.-P., & Soucail, G. 2002, A&A, 386, 31

Duc, P.-A., Poggianti, B.M., Fadda, D. et al. 2002, A&A 382, 60

Elbaz, D., Cesarsky, C.J., Chanial, P. et al. 2002, A&A 384, 848

Granato, G. L., Silva, L., Bressan, A., Lacey, C. G., Baugh, C. M., Cole, S., & Frenk, C. S. 2001, ApSSS, 277, 79

Kennicutt, R. C., 1998, ARA&A, 36, 189

Kessler, M.F., Steinz, J.A., Anderegg, M. et al. 1996, A&A 315, L27

Lémonon, L., Pierre, M., Cesarsky, C.J. et al. 1998, A&A 334, L21

Metcalfe, L., Kneib, J.-P.; McBreen, B.; et al. 2003, A&A, 407, 791 (Paper I)

Silva, L., Granato, G. L., Bressan, A., & Danese, L. 1998, ApJ, 509, 103

Smail, I., Kuntschner, H., Kodama, T. et al. 2001, MNRAS 323, 839

Treu, T., Ellis, R. S., Kneib, J., Dressler, A., Smail, I., Czoske, O., Oemler, A., & Natarajan, P. 2003, ApJ, 591, 53