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The envelope of the red galaxies distribution in a z = 0.75 cluster field*

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Abstract. We report the observation of a group of 16 red ($V - I > 2$) galaxies, in the magnitude range $22 \leq V \leq 25.5$, within a projected distance of 30″ ($\sim 0.2\ \mathrm{h}^{-1}$ Mpc for $h = H_o/75$ km s^{-1} Mpc^{-1}) of the ultra-steep spectrum radio source 1443-198 at $z = 0.753$. The colours of the galaxies range from the cut-off at $V - I = 2.0$ to $V - I = 3.3$. Eight galaxies are redder than $V - I = 2.3$ and three are redder than $V - I = 3.0$. Some objects with $I \approx 23$ are undetected at the magnitude limit of $V = 25.5$. This confirms previous results on the presence of a very red envelope in some distant clusters and suggests that a fraction of cluster ellipticals are already old at $z \approx 0.75$.

The radio galaxy has colours and a 4000 Å break amplitude typical of evolving E/S0 galaxies, and shows signs of interaction with other objects in its immediate vicinity.

Key words: galaxies: redshifts – galaxies: clusters – radio continuum: galaxies – galaxies: evolution – galaxies: G 1443-198

1. Introduction

The search for distant clusters of galaxies through their X-ray emission has been found to be probably the most efficient method today (Gioia et al. 1990; and references therein). Since it relies on the presence of hot intra-cluster gas, this technique assumes that the stage of formation of clusters was such that a dense and hot ICM was already formed. Present X-ray surveys seem to reach a detection limit at distances $z \sim 0.65$.

Nearby powerful radio galaxies are rarely found in dense galaxy environment but their presence in clusters significantly increases beyond $z \sim 0.4$ (Yates et al. 1989; Hill & Lilly 1991). An exemple of powerful radio galaxy in a rich cluster is 3C 34 at $z = 0.69$ (McCarthy 1988). Therefore the optical follow up of distant radio sources may be a way of discovering clusters beyond $z \approx 0.7$ complementary to X-rays. More precisely, since ultra-steep radio sources are known to often have a distant optical counterpart (Tielens et al. 1979; Gopal-Krishna and Steppe 1981) and the ICM can be an efficient medium for developing radio lobes (Fabian 1994), some fraction of ultra-steep radio sources should be found in distant clusters. In the course of our optical follow up of ultra-steep radio sources (Gopal-Krishna et al. 1992, 1995; Giraud 1991a; Melnick et al. 1993) we have indeed found several concentrations of galaxies beyond $z = 0.7$ (Giraud et al. 1996). The Molonglo 0.95 Jy radio source 1443-198 (Large et al. 1981) at $z = 0.753$ belongs to one of them. We report here preliminary observations of this object and its environment of red galaxies.

The redshift range $z = 0.7-0.8$ is particularly interesting for a photometric study of the evolution of red galaxies because the difference in $V-I$ colour index between a present-day elliptical projected at $z = 0.75$, i.e $V - I = 3.5$, and the ancestors of these galaxy types, $V - I = 2.2 - 2.3$ as inferred from evolutionary models (Bruzual 1988, 1990; Guiderdoni & Rocca-Volmerange 1988), is more than 1 mag. This large colour difference is a priori favourable for probing evolution and testing evolutionary tracks and world models.

The goal of this Letter is to show that there is a population of galaxies with $V - I > 2.3$ close to 1443-198, similar to that found by Ellis (1991) in another distant cluster (see also Giraud 1990a).

2. Observations and data reduction

The radio source 1443-198 was optically identified with a $R \approx 20.9$ galaxy located at $RA = 14^h43^m59^s; Dec. = -19^o51'06''(1950)$, on a 15 min R exposure, obtained with the

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3.6m telescope, in 1989. This image shows a rich field of faint galaxies which was subsequently observed during the commissioning period of the ESO New Technology Telescope (NTT). Photometric observations in V, R and I and a low resolution spectrum were obtained on March 4-5 and March 16-17, 1990, respectively, using EFOSC 2 (Melnick et al. 1989) equipped with a Thomson CCD chip of 1024 x 1024 pixels. The scale of the images is $0.15''$ per pixel with a total field of $150'' \times 150''$. The atmospheric conditions during the observations were excellent.

The present study is based on two R exposures of 900 s, two I exposures of 1200 s and 1380 s, two V exposures of 1888 s and 2400 s, and a low resolution spectrum of 6600 s. The photometry was calibrated using the galaxy cluster Cl 0500-29 (Giraud 1990b). The B, V, R, I photometry of this cluster used as standard, was acquired over the course of several runs between 1988 and 1990. Spectra of the two brightest galaxies were obtained with a grism having a dispersion of 136 Å mm^{-1} over the spectral range 5800 Å to 8400 Å, and a long slit with a width of $1.47''$ giving a resolution of 25 Å.

The images were corrected for flat field, using master flats obtained by median filtering of sky images. They were analysed separately using the INVENTORY context (Kruszewski, 1991) in MIDAS. The program creates a catalogue of parameters for each detected object which is used to classify them as galaxies, stars or defects. The FWHM of stars are $0.85''$ in V, $0.75''$ in R and $0.7''$ in I. With these FWHM values, the distinction between stars and galaxies is reliable up to $\sim$ 24mag, a value which is close to the limiting magnitudes, 24.5 in I, 25 in R and 25.5 in V. The analysis was performed independently for each colour, giving the possibility to compare the classifications of faint objects. Petrosian magnitudes (Petrosian 1976) were measured at η = 1.7 mag. The main advantage of Petrosian's system is that the magnitudes of objects at various z are measured at the same metric diameter. Because the images were not all taken at the same position angle, the overlapping field with V, R and I magnitudes is $127'' \times 90''$.

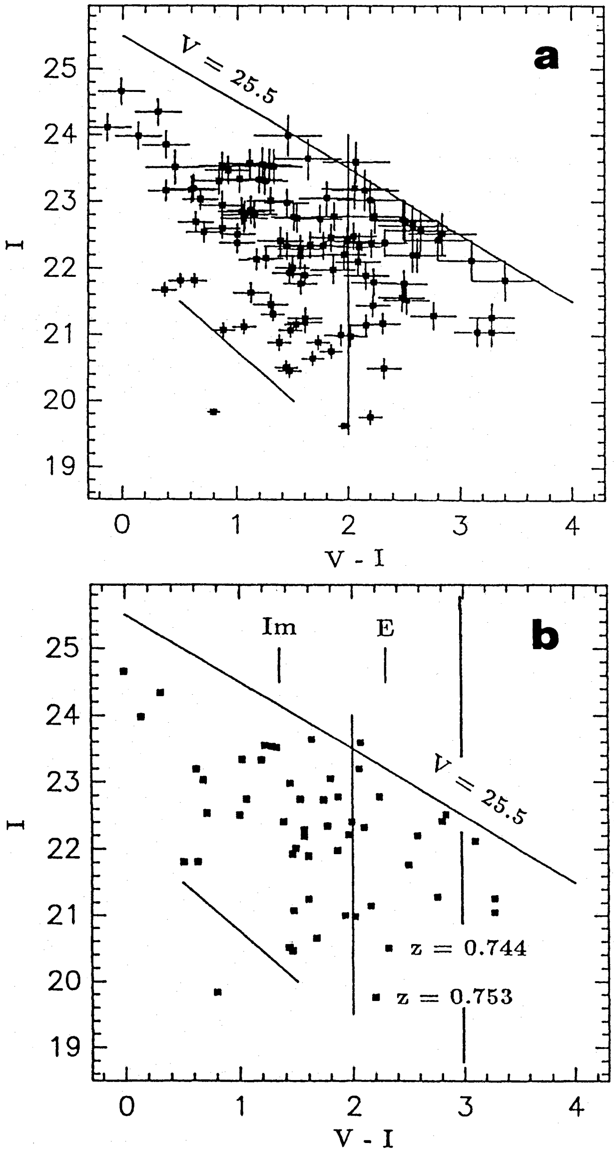

Fig. 1. A $[V-I, I]$ colour-magnitude diagram for all the detected objects brighter than $V \approx 25.5$, $R \approx 24.7$, $I \approx 24.5$ in the $127'' \times 91''$ field of 1443-198. Objects with $V - I > 2$ should be red galaxies at $z > 0.5$. **1b** - A $[V-I, I]$ colour-magnitude diagram for objects in a square of $60'' \times 60''$ centered on 1443-198. Magnitude limits and error bars are the same as for 1a. The two brightest red galaxies are labeled with their redshifts. The colours of evolving E and Im galaxies at z = 0.75 from Guiderdoni & Rocca-Volmerange (1988) models are indicated.

3. Observational results

3.1. Colour distribution of the 127 × 90″ *field*

A $[V-I, I]$ colour-magnitude diagram of the entire field is shown in Fig. 1a The immediate finding concerning this field is the extreme colour range of the detected objects from $V - I = 0$ to $V - I = 3.5$. This is strikingly similar to the colour-colour diagram found by Ellis (1991) where $V - I$ colours are found to range from 0.5 mag to 3.3 mag. We have compared with various control fields in regions void of apparent clusters. None contains such a density of galaxies with $V - I > 2$. From Table V of Guiderdoni & Rocca-Volmerange (1988) objects with such colours should be red galaxies at $z > 0.5$. The limiting magnitude of V = 25.5 poses a problem for the sampling of red objects (see the cut-off in Fig 1a). Some galaxies which are easily identified in I are not detected in V. To have a very good sampling of the red population would have required a limiting magnitude of V = 27. The projected spatial distribution of the red galaxies ($V - I > 2$) shows a clear concentration around the position of the radio source and a loose distribution over the field. Because the redshifts are unknown we restrict the study to a square field of $60'' \times 60''$ centered on the radio galaxy. The corresponding colour-magnitude diagram is shown in Fig. 1b.

3.2. Reddening

The reddening of this field, estimated from Burstein and Heiles (1982) maps is between $E(B-V) = 0.06$ and 0.09 mag. Adopting a value of $E(B-V) = 0.09$ mag yields $A_V = 0.28$ and $A_I = 0.14$. There is no reason for suspecting a local value higher than $E(B-V) = 0.09$. The spatial distribution of blue objects is uniform.

3.3. The radio-galaxy and its immediate neighbourg (Fig. 2)

The radio galaxy (G) has a redshift of z = 0.753. Its 4000Å break measured between 3750 – 3950 Å and 4050 – 4250 Å, following the definition of Hamilton (1985), has an amplitude of $D(4000) \approx 1.75$. The broad band colours of this object are $V-I = 2.20$, $V-R = 1.22$, $R-I = 0.98$. Galaxy A has a redshift of z = 0.744. The amplitude of its 4000Å break is $D(4000) \approx 1.85$ and the colours are $V-I = 2.32$, $V-R = 1.42$, $R-I = 0.90$. The colours of the two brightest objects are in reasonable agreement with their 4000 Å break amplitudes. The value of $D(4000)$ for these two objects is smaller than that of typical red galaxies at $z \approx 0.3$, for which we find typical values of ≈ 2 (67 red galaxies in 4 southern clusters). Their colours correspond to those of an evolving E/S0 galaxy at z = 0.75, according to evolutionary models (Bruzual 1988, Guiderdoni & Rocca-Volmerange 1988). The good correspondence between break and colours for these two objects suggests that the photometry is well calibrated ($V-I$ better than 0.2 mag). The $V-I$ colour of the radio galaxy is close to that of 0410-19 at $z = 0.794$ for which we measured a $V-I$ of 2.1 mag (Giraud et al. 1996). In 0410-19 we detected a very significant activity with the presence of a large emission line region, implying that this object may have bluer colours than a passively evolving elliptical at the same redshift. Since 1443-198 comes from the same list of ultra-steep radio sources, we can conceive that it presents some similarities.

The fact that 1443-198 is different from a present-day elliptical galaxy is supported by its apparent interaction with companion objects (Fig. 2). This image reveals the presence of very faint filaments that seems to radialy links the dominant galaxy to some of the surrounding galaxies located within a circle of 6″, which corresponds to $\sim$ 40 h^{-1} kpc where $h = H_o/75$ km s^{-1} Mpc^{-1} for a cosmology with $q_o = 0$. These apparent links are highly reminiscent of the filament seen between 0410-19 and its nearby companion both at rest in the potential well of an apparent cluster or forming cluster. The radio galaxy 1443-198 appears to be a good candidate of a first-ranked elliptical in the process of formation through accretion of surrouding material.

3.4. The $R = 30''$ region around 1443-198

At a cosmological distance of $z = 0.75$, a radius of 30″ corresponds to a linear distance $R = 0.2$ h^{-1} Mpc. If there is a cluster surrounding 1443-198 we are sampling its central region. Despite the bias introduced by the magnitude cutoff at $V = 25.5$, there are 16 galaxies with $V-I$ colour larger than 2, and 8 have

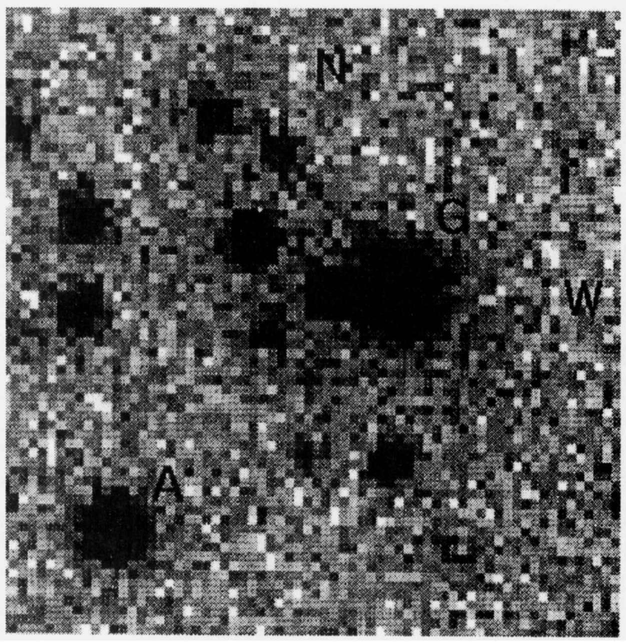

Fig. 2. A broad band image in I of the radio galaxy 1443-198. made from coddaing two frames of 1200 s and 1380 s (FWHM = 0.7″). The size of the image is 20″ × 20″. North is up, West is to the right. The frame is binned 2 x 2 to better show faint filaments that seem to radialy link the radio galaxy to some of its companion galaxies.

$V-I > 2.5$ i.e. the colours of present-day ellipticals. These 16 faint red galaxies in the close vicinity of the radio galaxy presumably trace a cluster core (hereafter called Cl 1443-198). The reddest object has $V-I = 3.3$ but there are only three galaxies with $V-I > 3.0$. Adopting a value of $V-I = 3.0$ for the "red envelope" is consistent with an error of 0.2 mag in the colour. It confirms the result of Ellis (1991; his Fig. 4) of a very "red enveloppe" of a cluster at similar redshift. Some cases of "red envelopes" at lower z have been previously discussed (e.g. Cl 0024+1654, Guiderdoni & Rocca-Volmerange 1988; references therein). Fig. 1d in Giraud (1991b) indicates a upper envelope of $V-I = 2.6$ for the Gunn et al. (1986) cluster Cl 0231+01 at $z = 0.567$. Very "red envelopes" are also consistent with the high upper limit of the 4000 Å discontinuity, at $z \leq 0.4$ (Dressler & Gunn 1990).

4. "Red envelope" and models

The $V-I$ colour difference between Bruzual (1988, 1990) or Guiderdoni & Rocca-Volmerange (1988) models of passively evolving E/S0 galaxies and the red envelope in Cl 1443-198 is 0.7 mag. In fact the 3 "red envelopes" of the quoted clusters at $z = 0.39$, $z = 0.57$ and Cl 1443-198 can be fitted by single burst models, where an initial period of star formation is followed by passive evolution. The advantage of these simplified models is to produce the reddest objects in the shortest time. More realistic models of E/S0 galaxies, with continuing star formation, tend to produce bluer colours. Redder colours can be obtained by increasing the age and metallicity, and changing the IMF.

4.1. A problem of age

Consider a 1 Gy single burst model (e.g. Guiderdoni & Rocca-Volmerange 1988) with classical IMF from Scalo (1986) and solar metallicity. All the initial gas is converted into stars in 1 Gy. The above evolution model indicates that a value of $V-I = 3.0$, measured on the continuum redshifted at $z = 0.75$, will be reached in 9.2 ± 0.5 Gy. This means that the age of the universe would be $t_{0.75} = 9.2 \pm 0.5$ Gy at $z = 0.75$, to which an period of galaxy formation should be added. The quoted error of ± 0.5 Gy means that colour differences cannot be distinguished over this range of ages. From these 9 Gy, we can deduce the present age of a flat universe as being between 17 Gy ($\Omega_o = 0.1$) and 21 Gy ($\Omega_o = 0.95$). Using these cosmological parameters, the single burst model gives $V-I = 2.65 - 2.7$ at $z = 0.56$, a value which compares well with the $V-I = 2.6$ envelope observed in Cl 0231+01. At $z = 0.56$, the object appears bluer because of the different redshift. A colour of $V-I = 2.6$ at $z = 0.56$ yields an age of $t_{0.56} = 10.2$ Gy for a single burst model and $17 \leq t_o \leq 20$ Gy. The positions of the "red envelope" in Cl 1443-189, i.e. $V-I = 3$, is marked in Fig. 1b, where the evolving E cold galaxy model from Guiderdoni & Rocca-Volmerange is also indicated. The difference between the E model and the envelope suggests a broad range of properties (IMF, metallicity, age) in addition to photometric errors for the red objects.

5. Discussion and conclusion

It has been recently established that a significant fraction of field galaxies should have experienced high rates of star formation at moderate redshift (review of Koo and Kron 1992). However, concerning the red population of galaxies in clusters up to $z \approx 0.5$, Hamilton (1985), Dressler (1987), MacLaren et al. (1988), Persson (1988) have noticed a "red envelope" to the colour distribution, whereby some galaxies have rest-frame colours of present-day elliptical. The existence of a significant fraction of star-forming galaxies in several clusters at $z = 0.2 - 0.5$ (Dressler & Gunn 1983; Henry & Lavery 1987; Couch & Sharples 1988; Gunn 1989, and references therein) nevertheless suggests that some form of evolution has been detected. The phenomenon is complex, however, and there is evidence that 1) it is not universal (Koo et al. 1988) and 2) the mode of activity varies from cluster to cluster (Dressler et al. 1985; Giraud 1990a). In fact in addition to any activity, clusters are very probably embeded in a field of the blue galaxies discovered by Tyson (1988) as can be inferred from the redshift surveys of Colless et al. (1990) and Lilly et al. (1991). A direct estimate of this effect is given by the interloper redshifts in cluster fields (Dressler & Gunn 1992)

Measurements of the 4000 Å break amplitudes, $D(4000)$, of galaxies in some clusters at $z = 0.70 - 0.75$ (Dressler and Gunn 1990) show that the upper "red envelope" has moved from $D(4000) \approx 2.5$ at $z < 0.5$ to $D(4000) \approx 2.1$ at $z \sim 0.7$, indicating that evolution of red objects has indeed been observed.

In this Letter we find that the $[V-I, I]$ colour magnitude diagram of a group of 16 red galaxies located near the radio source Molonglo 1443-198 at $z = 0.753$ has a red envelope of $V-I \approx 3.0$. This confirms previous results on the presence of a very red envelope in some less distant clusters and a similar finding by Ellis (1991) at large distance.

It seems that a fraction of cluster elliptical are already old at $z \approx 0.75$.

A single burst model with a classical IMF and solar metallicity can reproduce the colour of the red envelope giving a rather old age of $t_{0.75} \approx 9$ Gy.

The radio galaxy has colours and 4000 Å break amplitude typical of evolving E/S0 galaxies and shows signs of interaction with other objects in its immediate vicinity. A comprehensive study of this object including (i) the state of ionization of the gas, (ii) a map of the emission-line nebula, (iii) a search for a hot intracluster medium through X-ray observations, (iv) deep imaging to analyse the interaction between the central galaxy and its companions, (v) an analysis of the interplay between the radio lobes and the ambiant medium, would certainly give clues on the formation of a first-ranked elliptical galaxy through accretion of surrounding material.

References

Bruzual A.G., 1988, in: Kron R.G., Renzini A. (eds) Towards Unserstanding Galaxies at Large Redshift, Kluwer, Dordrecht, p.161

Bruzual A.G., 1990, in: Kron R.G. (ed) Evolution of the Universe of Galaxies, PASPC 10, 185

Burstein D., Heiles C., 1982, AJ 87, 1165

Colless M., Ellis R.S., Taylor K., Hook R.N., 1990, MNRAS 244, 408

Couch W.J., Sharples R.M., 1988, MNRAS 229, 423

Dressler A., 1987, in: Faber (ed) Nearly Normal Galaxies from the Planck Time to the Present, Springer, New York, p. 265.

Dressler A., Gunn J.E., 1983, ApJ 270, 7

Dressler A., Gunn J.E., Schneider D.P., 1985, ApJ 294, 70

Dressler A., Gunn J. E., 1990, in: Kron R.G. (ed) Evolution of the Universe of Galaxies, PASPC 10, 200

Dressler A., Gunn J.E., 1992, ApJS 75, 1

Ellis R.S., 1991, in: Bohringer H., Treumann R.A. (eds) Traces of the Primordial Structure in the Universe, Garching, MPE report 227, p.101

Fabian A.C., 1994, ARA & A 32, 277

Gioia I. M., Maccaro T., Schild R., Wolter A., Stocke J., and Morris S., 1990, ApJS 72, 567

Giraud E., 1990a, The ESO Messenger 62, 45

Giraud E., 1990b, A&AS 83, 1

Giraud E., 1991a, A&A 252, L5

Giraud E., 1991b, A&A, submitted

Giraud E., Melnick J., Gopal-Krishna, Mendes de Oliveira C., Kulkarni K., 1996, A&A accepted

Gopal-Krishna, Steppe, H., 1981, A&A 101, 315.

Gopal-Krishna, Giraud E., Melnick J., Steppe H., 1992, A&A 254, 42

Gopal-Krishna, Giraud E., Melnick J., della Valle M., 1995, A&A 303, 705

Guiderdoni B., Rocca-Volmerange B., 1988, A&AS 74, 185

Gunn J.E., Hoessel J.G., Oke J.B., 1986, ApJ 306, 30

Gunn J.E., 1989, in: Frenk et al. (eds) The Epoch of Galaxy Formation, Kluwer, Dordrecht, p.167

Hamilton D., 1985, ApJ 297, 371
Henry J.P., Lavery R.J., 1987, ApJ 323, 473
Hill G.J., Lilly S.J., 1991, ApJ 367, 1
Koo D.C., Kron R.G., 1992, ARA&A 30, 613
Koo D.C., Kron R.G., Nanni D., Trevese D., Vignato A., 1988, ApJ 333, 586
Kruszewski A., in: MIDAS Users Guide, 1991, Image Processing Group, ESO
Large M.I., Mills B.Y., Little A.G., Crawford D.F., and Sutton J.M., 1981, MNRAS 194, 693
Lilly S.J., Cowie L.L., Gardner J.P., 1991, ApJ 369, 79
MacLaren I., Ellis R.S., and Couch W.J., 1988, MNRAS 230, 249
McCarthy P. J., 1988, PhD Thesis, University of California, Berkeley
Melnick J., Altieri B, Gopal-Krishna, Giraud E., 1993, A & A 271, L8
Melnick J., Dekker H., D'Odorico S., 1989, ESO Operating Manual No 4, Garching
Persson E., 1988, in: Kron R., Renzini A. (eds) Towards Understanding Galaxies at High Redshifts, Kluwer, Dordrecht, p.251
Petrosian V., 1976, ApJ 209, L1
Scalo J.M., 1986, Fund. Cosm. Phys. 11, 1
Tielens, A.G., Miley, G.., Willis, A., 1979, A&AS 35, 153.
Tyson J.A., AJ 96, 1
Yates M.G., Miller L., Peacock J.A., 1989, MNRAS 240, 129

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