tion of the middle-aged PSR B0656+14 and Geminga, including possible atmospheric cyclotron lines. A joint fit of the optical/X-ray thermal components would provide a better measurement of the observed neutron star surface temperature, important to investigate both its internal structure and the physical/chemical properties of its atmosphere. On the other hand, fitting well-resolved cyclotron lines would allow to obtain the first direct measurements of the neutron star magnetic field (Bignami 1998). For Geminga, a spectrum was recently obtained from the ground (Martin et al. 1998) but with a very low S/N, while no spectroscopy observation has yet been tried for the slightly brighter PSR B0656+14.

To pursue all the above goals, deep imaging, timing and spectroscopic observations, as feasible with 8-m-class telescopes, are required. Needless to say, in all cases the VLT could offer an invaluable contribution. In particular, with FORS1 and FORS2, both Antu and Kueyen fulfil the imaging/spectroscopy requirements. On the other hand, timing observations can be performed either by using FORS2 in trailer mode (see e.g. ESO/PR 17/99) or by using MAMA detectors attached to the visitor focus of Yepun. Thus, we can certainly say that the VLT has all the potentialities to open a new era in the optical astronomy of pulsars, giving back to ESO the leadership achieved before the advent of the HST.

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The ROSAT Deep Cluster Survey: Probing the Galaxy Cluster Population out to z = 1.3

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1. Introduction

The redshift evolution of the space density of galaxy clusters has long served as a valuable tool with which to test models of structure formation and to set constraints on fundamental cosmological parameters. Being recognisable out to large redshifts, clusters are also ideal laboratories to study the evolutionary history of old stellar systems, such as E/S0s, back to early cosmic look-back times. It is therefore not surprising that a considerable observational effort has been devoted over the last decade to the construction of homogeneous samples of clusters over a large redshift baseline. Until a few years ago, however, the difficulty of finding high-redshift clusters in deep optical images and the limited sensitivity of early X-ray surveys had resulted in only a handful of spectroscopically confirmed clusters at $z > 0.5$. The ROSAT satellite, with its improved sensitivity and spatial resolution, made clusters high-contrast, extended objects in the X-ray sky and has thus allowed for a significant leap forward. About a thousand clusters have now been selected from the ROSAT

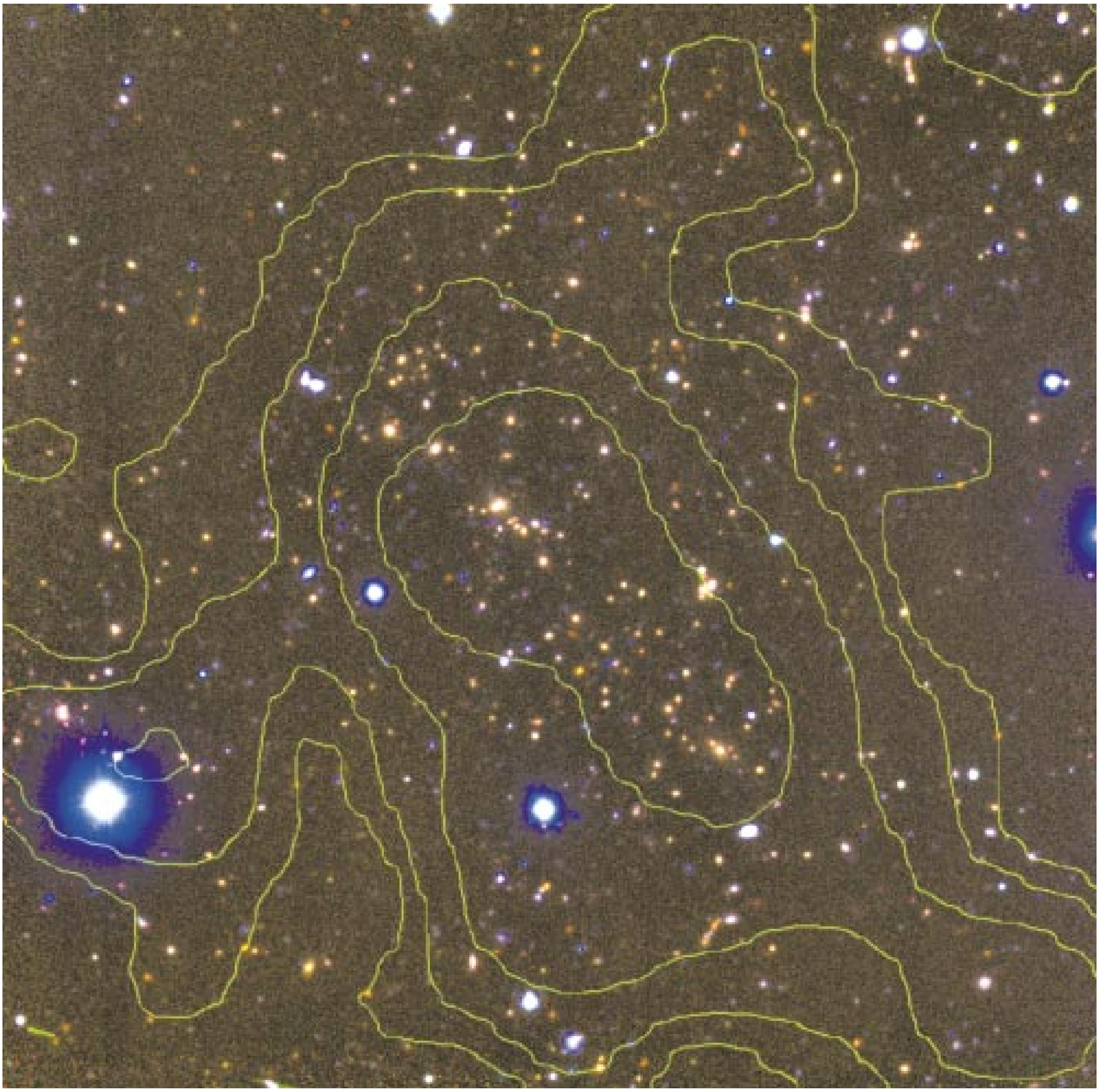


Figure 1: RXJ0152.7-1357 (z = 0.83) – one of the most X-ray luminous clusters known at z > 0.5. The ROSAT PSPC X-ray contours are overlaid on a (V+R, J, K) composite image obtained with VLT/FORS1 and NTT/SOFI. The field of view is 4.7′ × 4.7′ (corresponding to 2.3 Mpc h_{50}^{-1} at z = 0.83). The overall morphology of the X-ray emission, and the apparent galaxy distribution, are clearly elongated with two clumps present.

All-Sky Survey at $z \gtrsim 0.3$ and several statistical complete subsamples have been used to obtain a firm measurement of the local abundance of clusters and their spatial distribution (cf. Böhringer et al. 1998). Soon after the ROSAT archive of pointed observations was opened, it was realised that deep PSPC pointings could be used for serendipitous searches for distant clusters.

In this spirit, we embarked in 1994 on the ROSAT Deep Cluster Survey with the aim of constructing a large, X-ray flux-limited sample of distant galaxy clusters. In the period 1995–1998 we engaged in an intense optical identification programme, a substantial fraction of which was carried out with the EFOSC spectrograph at the 3.6-m at La Silla. Over the last two years, our efforts have shifted to the near IR study of the most distant candidates and, most recently, to spectroscopic follow-up of these systems with the VLT. This observational effort has produced the largest sample of spectroscopically-confirmed distant clusters to date, with four clusters confirmed beyond redshift one. We summarise here some results and highlights from the entire survey.

2. Cluster Selection and the Optical Follow-up Work

The RDCS was designed to compile a purely X-ray selected sample of galaxy clusters, selected via a serendipitous search for extended X-ray sources in ROSAT-PSPC deep pointed observations (Rosati et al. 1995). The limiting X-ray flux and the solid angle of the survey were chosen to probe an adequate range of X-ray luminosities over a large redshift baseline. Approximately 160 candidates were selected down to the flux limit of 1×10^{-14} erg s^{-1} cm^{-2}, over a total area of ~ 50 deg^2, using a wavelet-based detection technique. This technique is particularly efficient in discriminating between point-like and extended, low surface brightness sources.

Optical follow-up observations of the cluster candidates in both hemispheres consisted primarily of optical imaging in the I-band with 2- and 4-m-class telescopes at NOAO and ESO, followed by multi-object spectroscopy with 4-m-class telescopes at KPNO and ESO. Candidates were observed in order of decreasing X-ray flux to have a flux-limited sample at any given time. EFOSC at the 3.6-m was used for the identification of the southern and equatorial clusters, and indeed, it proved to be an ideal instrument for this work. Typically, a 10-minute snapshot image was obtained and if a galaxy overdensity was visible around the X-ray peak, a MOS exposure was obtained the following night. Even with the old IHAP system, overheads were relatively small and mask alignment very reliable. This contributed to the overall efficiency of identification, and approximately 60 southern cluster redshifts were secured over 3 years with 20 allocated nights (80% clear). About a quarter of these clusters were confirmed at $z > 0.5$. The highest redshift cluster (RXJ0152.7-1357) was identified with EFOSC1 at $z = 0.83$ (Rosati et al. 1998, Della Ceca et al. 2000). This cluster, shown in Figure 1, is one of the most X-ray luminous known at $z > 0.5$ and possibly also one of the most massive distant systems, perhaps akin to MS1054.4-0321 (Gioia & Luppino 1994).

To date, the entire RDCS sample contains 115 new clusters or groups with secure spectroscopic redshifts, 21 of which lie at $z > 0.6$ and 10 at $z > 0.8$. The redshift distribution is shown in Figure 2 and compared with the EMSS cluster sample, which has been the basis of numerous studies of distant clusters in previous years. The RDCS has clearly considerably extended the high-redshift tail.

The spectroscopic identification is 90% complete to 3×10^{-14} erg s^{-1} cm^{-2}; at this limiting flux, the completeness level and the selection function are both well understood. At fainter fluxes, the effective sky coverage progressively decreases and the X-ray surface brightness limit becomes increasingly important. However, it is precisely in this lowest flux bin that the most distant clusters of the survey are expected to lie. To improve the success rate of identifying $z \gtrsim 1$ clusters, we have begun a programme of near-IR imaging of unidentified faint candidates in the RDCS. Near-IR imaging is essential at these large redshifts to compensate the k-correction, which significantly dims the dominant population of early-type cluster galaxies at observed optical wavelengths. A dramatic example of this effect is illustrated in Figure 3. A deep I-band image with a 4-m-class telescope (CTIO 4-m) had not shown any significant galaxy overdensity at the X-ray position. On the other hand, a moderately deep image with SOFI at the NTT (bottom right) clearly revealed a red clump of galaxies with a narrow $J - K$ colour distribution typical of early-type galaxies at $z > 1$ (see the “yellow clump” in the colour composite image). The same clump is barely visible in a 1-hour R-band exposure with FORS1 (bottom left). Cluster galaxies are fainter than $K = 17$, with colours as red as $R - K = 6$. FORS1 spectroscopy in March 1999 yielded a redshift $z = 1.23$ for the 3 brightest cluster members, and further spectroscopic work is scheduled with FORS1 in March 2000. It is worth emphasising that spectroscopy of early-type galaxies at these redshifts is extremely hard, even with the VLT, requiring no less than 5 hours integration to securely identify a few absorption features (primarily the H+K break) embedded in the OH sky forest. The cluster in Figure 3 is the highest redshift cluster confirmed to date in the southern sky. Three other RDCS clusters in the northern sky were spectroscopically identified with the Keck telescope at $z > 1$ (Stanford et al. 1997, Rosati et al. 1999).

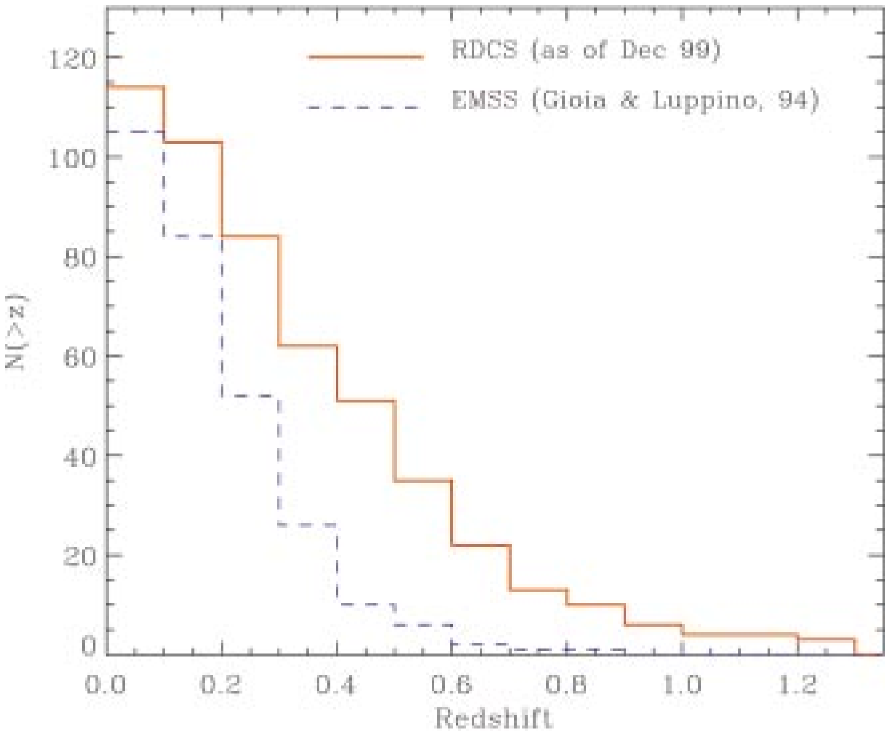


Figure 2: The cumulative redshift distribution of spectroscopically confirmed RDCS clusters to date. For comparison, the distribution of the EMSS sample (Gioia & Luppino, 1994) is shown.

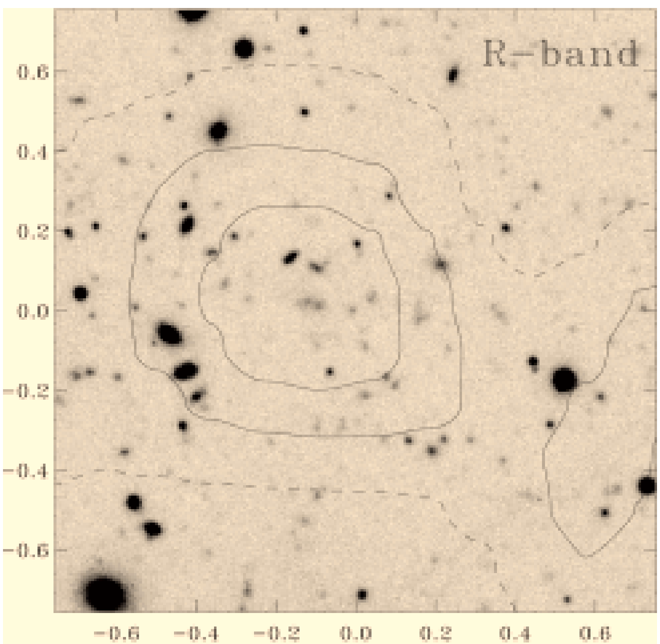
3. Some RDCS Highlights

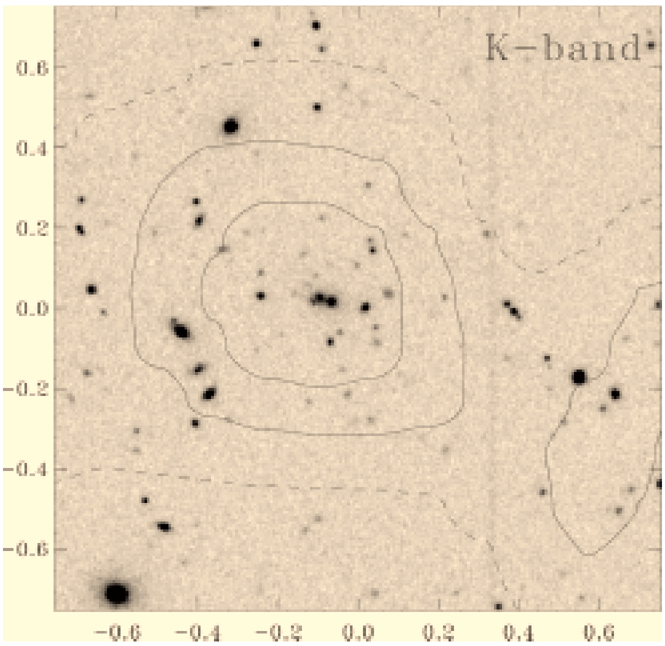
An immediate advantage of an X-ray selected cluster sample, like the RDCS, is that one can use statistics such as number counts and luminosity functions to quantify the evolution of the cluster population, similar to what is done for galaxy redshift surveys. In Figure 4, we show the X-ray luminosity function (XLF, i.e. the number of clusters per comoving Mpc^3, per unit X-ray luminosity) of a complete, spectroscopically identified RDCS subsample with a limiting flux of 3.0×10^{-14} erg s^{-1} cm^{-2}. This represents the best determination to date of the space density of distant clusters out to $z \simeq 1.2$. A maximum likelihood analysis of the sample confirms the visual impression that there is no significant evolution of the cluster space density out to $z \simeq 1$, at luminosities below the local L^*_X ($\approx 4 \times 10^{44}$ erg s^{-1} [0.5–2 keV], roughly the Coma cluster). Careful analysis of the bright end of the XLF instead shows some mild negative evolution, i.e. a lack of the most luminous, possibly massive systems ($L_X \gtrsim 4 \times 10^{44}$ erg s^{-1}) at high redshifts. This result is consistent with the original findings of the EMSS (Gioia et al. 1990), although the strength of the effect is still a matter of some debate (Rosati et al. 1998, 1999).

The identification of the most distant clusters in the RDCS allows an estimate of the cluster abundance to be made for the first time at $z \approx 1$. This is shown in Figure 4 as a lower limit due to the incomplete optical identification at very low flux levels. According to this estimate, there is at least one cluster as luminous as 1/5 of the Coma cluster in $(150 h_{50}^{-1})^3$ Mpc^3 comoving, at $z \simeq 1$.

▶
Figure 3: RJK composite image of the most distant RDCS cluster in the southern sky ($z = 1.23$) obtained combining FORS1 and SOFI images. The field of view is 3.8′ × 3.8′. Bottom: R-band and K-band image obtained with VLT/FORS1 and NTT/SOFI (1 hour exposure each), with overlaid ROSAT-PSPC contours (scale in arcmin).


R - VLT/FORS
J,K - NTT/SOFI


R-band
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.6 -0.4 -0.2 0.0 0.2 0.4 0.6


K-band
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.6 -0.4 -0.2 0.0 0.2 0.4 0.6

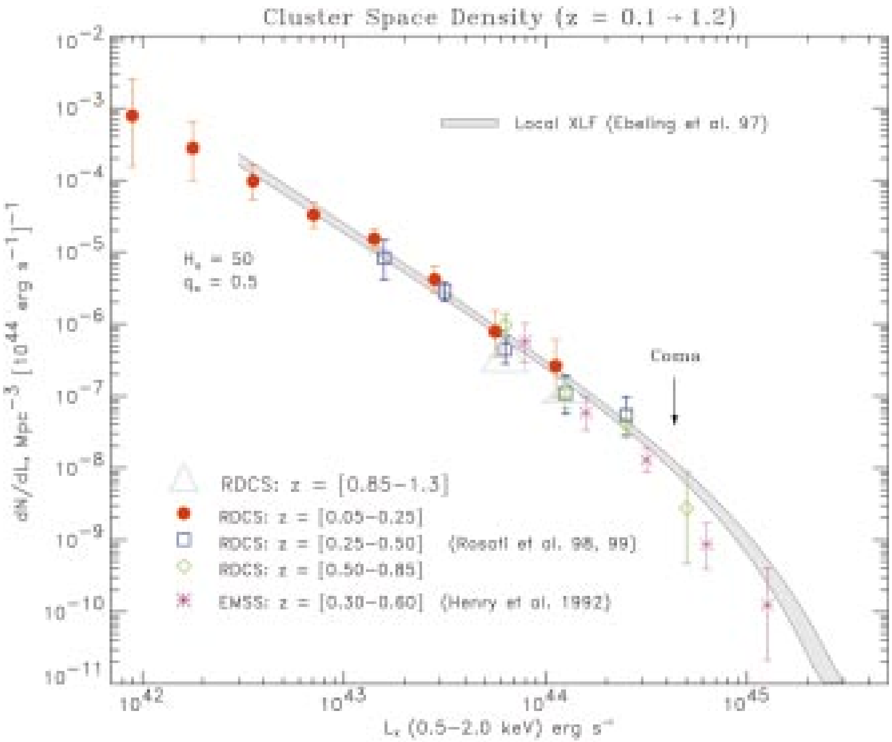


Figure 4: The best determination to date of the cluster X-ray Luminosity Function out to $z \approx 1.2$. Data points at $z < 0.85$ are derived from a complete RDCS sample of 103 clusters over 47 deg^2, with $F_{lim} = 3 \times 10^{-14}$ erg s^{-1} cm^{-2}. The triangles represent a lower limit (due to incomplete optical identification) to the cluster space density obtained from a sample of 4 clusters with $\langle z \rangle = 1.1$ and with $F_{lim} = 1.5 \times 10^{-14}$ erg s^{-1} cm^{-2}.

That the space density of the bulk of the cluster population is approximately constant out to $z \simeq 0.8$ has interesting consequences for cosmology. Despite the fact that we are not measuring cluster masses but X-ray luminosities, which depend of the thermodynamical history of the intra-cluster gas in a complicated fashion, it can be shown that significant constraints can be placed on cosmological models within the uncertainties of the $L_X - M$ relation and its evolution (see Fig. 5, Borgani et al. 1999a, 1999b). This analysis shows that it is difficult to reconcile an $\Omega_M = 1$ universe with the RDCS data and our current knowledge of the $L_X - T_X$ relation for distant clusters. The fact that a large fraction of relatively massive clusters is already in place at $z \sim 1$ indicates that the dynamical evolution of structure has proceeded at relatively slow pace since $z \simeq 1$, a scenario which fits naturally in a low-density universe.

4. Conclusions

The sheer number of distant clusters spectroscopically identified in the RDCS illustrates the efficiency of the methodology used, as well as the strategy of the optical follow-up observations which were largely carried out with 4-m-class telescopes. By boosting the number of known clusters at $z > 0.5$ by a factor 5, the RDCS provides the basis for several follow-up studies. Some of these programmes, such as the evolution of the cluster galaxy populations and the cluster mass distribution via lensing and dynamical methods, have already begun with the VLT.

In particular, the spectrophotometric properties of cluster galaxies at $z > 1$ are important diagnostics for constraining the mode and epoch of formation of E/S0 galaxies. The near-IR colours of the reddest members of the RDCS clusters which we have studied so far at $z > 1$ show that these galaxies form a remarkably homogeneous population, a property which is often exploited to constrain the formation scenario of E/S0s (e.g. Stanford et al. 1997). Deep ISAAC imaging would be crucial to investigate the (unknown) faint end of the cluster galaxy population at several magnitudes below L^*, at these high redshifts. The time-consuming spectroscopic work will benefit considerably from the planned upgrade of FORS2 with a red-sensitive CCD, coupled with high-throughput gratings.

Many exciting new observations of these clusters will be made in the near future. Further insight on the physical properties (temperature, metallicity) of the gaseous component of the most distant RDCS clusters will be possible with scheduled Chandra and XMM observations. In addition, significant progress towards our understanding of the formation of the galaxy populations at these large look-back times will come from combining VLT data with planned observations of these clusters with the Advanced Camera on HST (scheduled in 2001).

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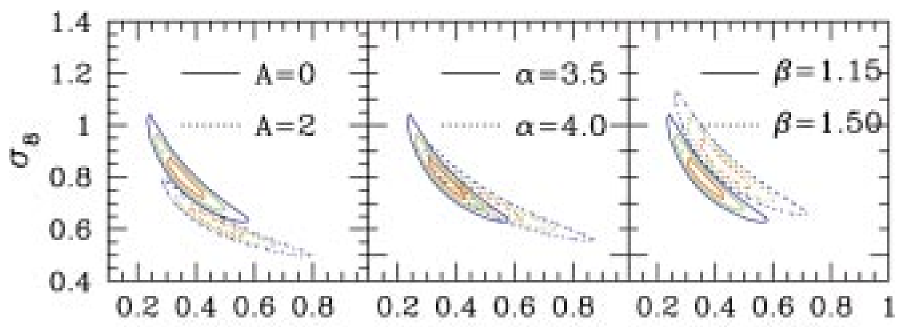

Figure 5: Constraints in the plane of the cosmological parameters Ω_0 (matter density parameter)–σ_8 (rms mass fluctuation on a 8h^{-1} Mpc scale) derived from the observed evolution of the cluster abundance in the RDCS sample (Borgani et al. 1999a, 1999b). Contours are 1σ, 2σ and 3σ confidence level. The three parameters (A, α, β) describe the uncertainties in converting cluster masses into temperatures ($T \sim M^{2/3} / \beta$), and temperatures into X-ray luminosities ($L_X \sim T^{\alpha} (1 + z)^A$). The two values for each parameter bracket the range which is allowed from current X-ray observations of distant clusters.