Clusters of Galaxies

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Introduction

The large-scale structure of the universe is dominated by clustering. Most galaxies seem to be members of pairs, groups, clusters, and superclusters. To that degree we are able to recognize a hierarchical structure of the universe. Our local group of galaxies (LG) is centred on two large spiral galaxies: the Andromeda nebula and our own galaxy. Three smaller galaxies – like M 33 – and at least 23 dwarf galaxies (Kraan-Korteweg and Tammann, 1979, *Astronomische Nachrichten*, **300**, 181) can be found in the evironment of these two large galaxies. Neighbouring groups have comparable sizes (about 1 Mpc in extent) and comparable numbers of bright members. Small dwarf galaxies cannot at present be observed at great distances.

Kraan-Korteweg and Tammann associate at least two thirds of the galaxies within 10 Mpc with groups. Other authors give even lower limits to "field" galaxies down to only 1 % (Huchra and Thuan, 1977 *Astrophysical Journal*, **216**, 694) on the basis of 1,088 galaxies). The relative proportions of the two populations (field and cluster members) and the difference in their global properties should help in determining the relative influence of the environment on the formation and evolution of a galaxy. Peebles' (1974 *Ap. J.*, **189**, L51) theory of the formation of clusters of galaxies from the gravitational instability of the early universe suggests that all galaxies should be clustered on all scales and there should be no homogeneous component. This prediction cannot definitively be tested owing to the difficulty in determining the membership of individual galaxies even if good radial velocities are available.

The Nearest Rich Clusters

The nearest rich cluster is the Virgo cluster at a distance of 15–20 Mpc. Its main body covers an area of 6° in diameter on the sky, corresponding to a linear extent of 2 Mpc. Its mean radial velocity (corrected for the rotation of our galaxy) is $v_0 \sim$ 1,100 km/s. The velocity dispersion is 556 km/s for E and S0 galaxies and 821 km/s for spiral galaxies. These values were derived from about 50 galaxies each. The lower velocity dispersion of the T and S0 galaxies and their greater concentration to the centre of the cluster show that early-type galaxies dominate the inner part of this cluster. Spirals are predominantly found in the outer parts. The more or less smooth distribution of spirals across the area of the Virgo cluster is obviously a projection effect. Beyond the inner 6°, the structure of the Virgo cluster becomes irregular. Outside a circle of 15° diameter, several "clouds" of galaxies are found. The Virgo cluster and all groups from its environment form the local supercluster. This is an elongated and flattened system of

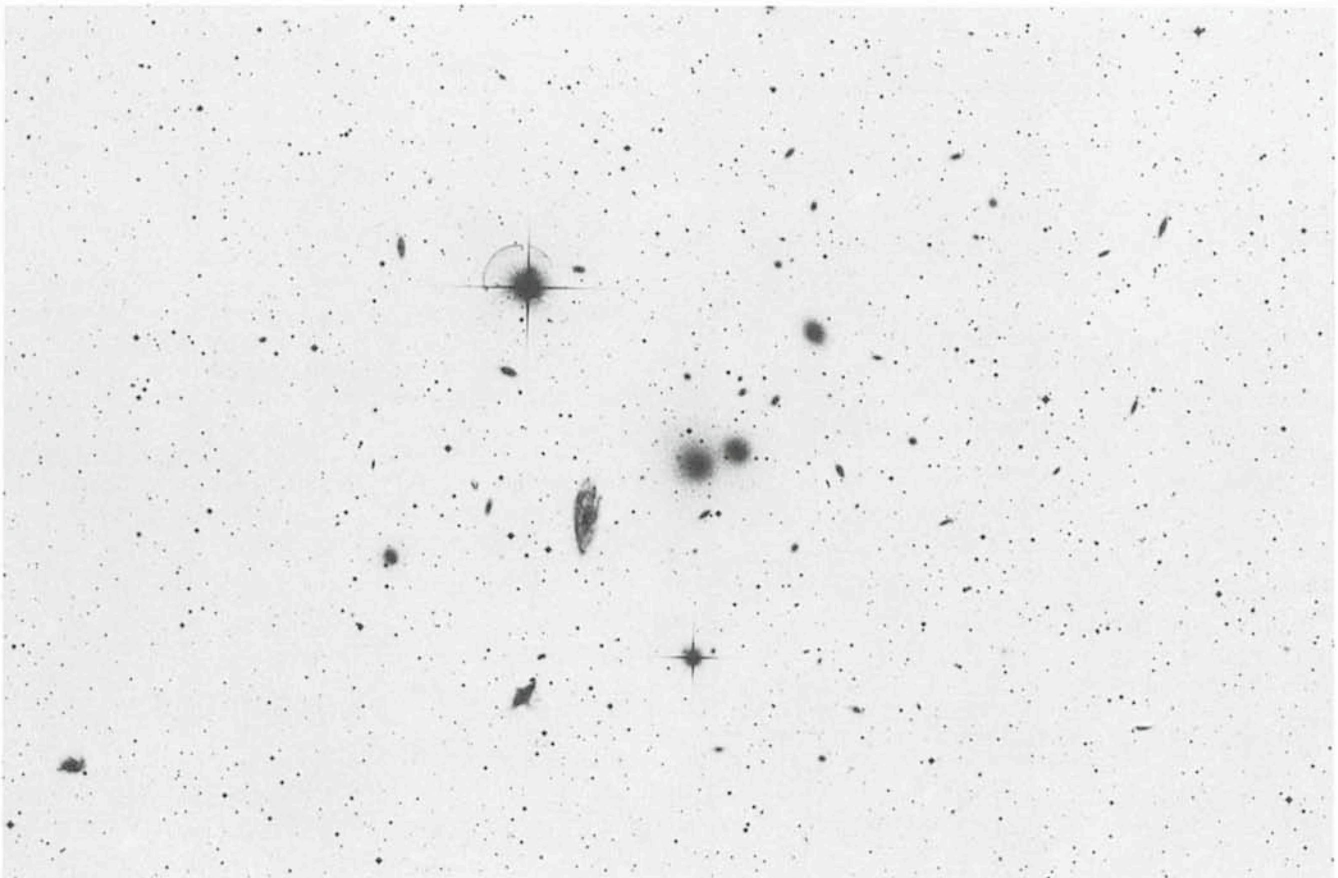

Fig. 1: *Central area of the Hydra I cluster of galaxies (reproduced from the ESO B survey). The angular separation of the two central spherical galaxies NGC 3309 (type E1) and NGC 3311 (S0) is 1.′6.*

roughly 25–30 Mpc in length and 15 Mpc in width. Most members lie within a few Mpc of the supercluster plane.

Beyond the Virgo cluster, Hydra I (= Abell 1060) is the next in the sequence of spiral-rich clusters (Fig. 1). It has Abell distance class O and richness class 1 and is situated at the eastern edge of the Hydra-Centaurus supercluster. Zwicky first published diagrams of the distribution of its galaxies (1941, *Proc. Nat. Acad. Sci.*, **27**, 264). From the observed apparent luminosity function he derived a radial velocity of about 4,000 km/s for the cluster, on the assumption of a constant absolute magnitude for the brightest galaxies in clusters. This value is in reasonable agreement with the radial velocity of 3,400 km/s, derived from our observations in Chile.

The next rich cluster is the regular Coma cluster at a distance of about 90–130 Mpc (v_0 = 6,900 km/s) which is dominated by early-type galaxies (E/S0). The main body of the Coma cluster is contained within a radius of 100′ (about 4 Mpc). It is generally assumed that, initially, galaxies of different masses have the same distribution law within a given cluster. Massive galaxies will experience a deceleration due to two-body encounters resulting in mass segregation. In fact, in the central part of the Coma cluster a significant amount of mass segregation is found among the brightest members ($M > 10^{12} M_\odot$). Outside this inner part the Coma cluster becomes asymmetric. To the west, an irregular supercluster seems to extend out to about 14° (nearly 35 Mpc). Galaxies at such distances have not had time to cross the centre of the cluster, and should therefore roughly reflect the initial conditions of cluster formation.

A structure like that of the Coma cluster is typical for rich regular clusters. Core radii seem to have the same linear values of about 0.4 Mpc for all rich clusters. The centres of rich clusters are often dominated by giant elliptical galaxies: M 87 in Virgo or NGC 4889 in Coma. Several classification schemes have been developed (for a review see e.g. Bahcall, 1977, *Ann. Rev. Astron. Astrophys.*, **15**, 505). Some depend on morphology, others on the dominance of bright galaxies or on the galaxy content of clusters. To enter Abell's catalogue, a cluster has to have more than 50 members within a radius of $3 \cdot h_{50}^{-1}$* Mpc, which are brighter than the magnitude of the third brightest galaxy plus two magnitudes. Abell's catalogue contains a total of 2,712 clusters north of declination – 27°5.

Galaxy counts within concentric rings around the cluster centre yield the projected surface density distribution and thus information about the relative concentration towards the centre and the regularity of the cluster structure. With the assumption of spherical symmetry the measured surface density can be used to calculate the space density. Such information is available for nearly 150 clusters. More detailed studies, for example of mass segregation and of the distribution of galaxy types, are possible with additional information about morphological types and apparent magnitudes of individual member galaxies. A well defined relationship is found between local galaxy density and the distribution of galaxy types, namely an increasing elliptical and S0 population and a corresponding decrease in spirals with increasing density.

Galaxy counts in the Hydra I cluster (Kwast, 1966, *Acta Astron.*, **16**, 45) show a sharp peak of the galaxy density distribution in the centre, stronger than can be explained by an Emden isothermal gas sphere model. Additional information can be obtained from radial velocity measurements. Cluster membership can only be discussed if radial velocities are known. Thus many redshifts are necessary for the computation of elaborate models. Unfortunately the greatest shortage in available data is that of redshifts. Radial velocities of cluster galaxies tell us something about kinematics, which in principle yields information about the gravitational potential, masses, and forces. At present, reasonable numbers of radial velocities – i.e. for more than about 20% of all member galaxies – are available only for very few clusters, among which are those of Virgo, Coma, and Hercules.

* $h_{50} = H_0/50$ km s^{-1} Mpc^{-1}, H_0 = Hubble constant.

Fig. 2: *A close-up view of the two peculiar spirals NGC 3312 (top) and NGC 3314 (bottom), the latter being a superposition of two spiral galaxies. This 25 min. exposure with the ESO 3.6 m telescope was made on baked IIIa-J + GG 385.*

As early as 1937 Zwicky realized the "missing-mass" problem when applying the virial theorem to clusters of galaxies. The total mass of clusters derived this way is about 1 to 2 orders of magnitude greater than the sum of the masses of individual galaxies. The missing mass cannot be hidden in the observed galaxies as two-body relaxation then would be fast enough to produce substantial equipartition of energy between light and massive galaxies. Intergalactic gas (neutral gas is not observed) manifests its presence by radio continuum and X-ray emission in a number of clusters. The amount of gas is hardly comparable to the mass observed in galaxies and thus does not solve the missing-mass problem.

The Hydra I Cluster: Description

In a project to study the properties of nearby medium-sized clusters we observed the Hydra I cluster (Abell 1060), which lies at R.A. 10^h34^m and DEC. – 27°16′, using the ESO 1.52 m and 3.6 m telescopes and the 100 m radio telescope of the MPIfR at Effelsberg. The high percentage of spiral galaxies is already evident from Fig. 1. This was one of the reasons to include Hydra I in our project, the aim of which was to derive radial velocities of the spiral galaxy population from 21 cm line observations of neutral hydrogen (HI), to complete the sample of radial velocities, to derive global parameters of the spirals from the HI observations for a detailed comparison with global parameters of the "local sample" of spiral galaxies, i.e. with galaxies not in clusters, and to study the influence of the cluster environment on the evolution of galaxies. Spiral galaxies in Hydra I contribute about 50 % to the total galaxy content. The ratio of spiral to elliptical galaxies increases from 0.2 in the centre up to a value of 4 at a radius of about 4 Mpc. The dwarfs and low surface brightness galaxies follow the spatial distribution of the E-galaxy population. The spirals in the dense part of the cluster are "anemic", lacking gas and star formation as indicated by their reddish colour. This is in agreement with low upper limits of neutral hydrogen. Within the main body of Hydra I upper limits to the M_{HI}/L ratio of these spirals are of the order of 0.2 or less, compared with an expected $M_{HI}/L \sim 0.4$. For NGC 3312 the corresponding value is ≤ 0.06. In contrast, a few spirals on the periphery of Hydra I show a normal HI content. In addition, spirals in the Virgo cluster are HI deficient by a factor of about 2 on the average. Observations of some spirals in the Coma cluster and in Abell 1367 show an HI deficiency by a factor of at least 4 (Sullivan and Johnson, 1978, *Ap. J.*, **225**, 751).

The gravitational centre of Hydra I is close to the two spherical galaxies in the centre, NGC 3309 (E1) and NGC 3311 (S0) (right and left respectively). A large-scale photograph of these two galaxies was already shown in the MESSENGER No. 10. Hydra I is classified by Bautz and Morgan as a type-III cluster and by Rood and Sastry as a type-C cluster, implying a core-halo structure with no dominant galaxy. Hydra I is a cluster X-ray source with a luminosity $L_x \sim 2 \cdot 10^{43}$ erg/s (in the 2–10 keV range). Solinger and Tucker (1972, *Ap. J.*, **175**, L107)

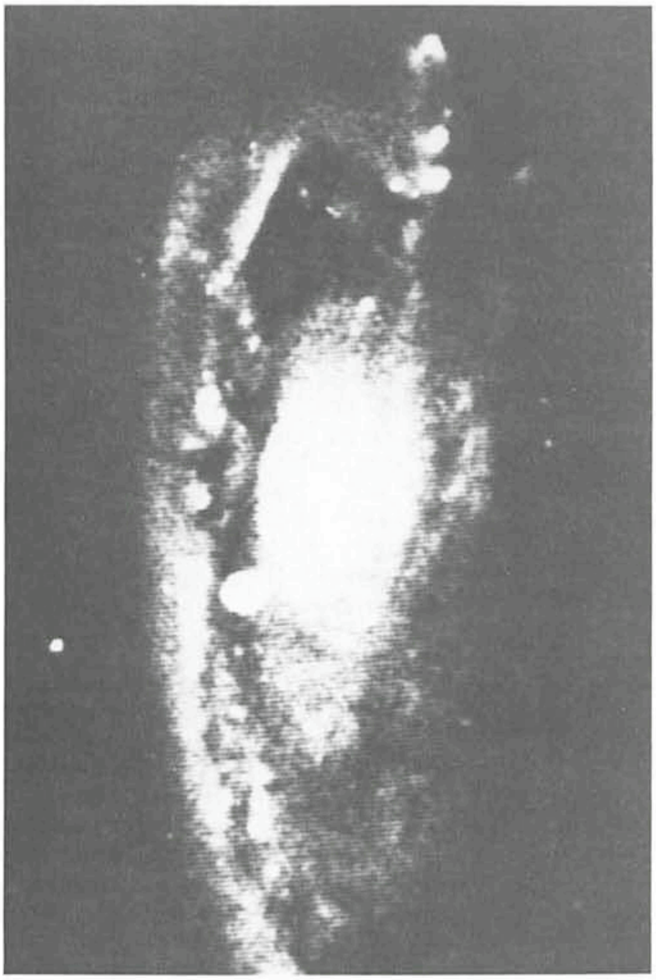

Fig. 3: *The isodensitometry of NGC 3312 shows an enlarged and contrast-enhanced version of Fig. 2.*

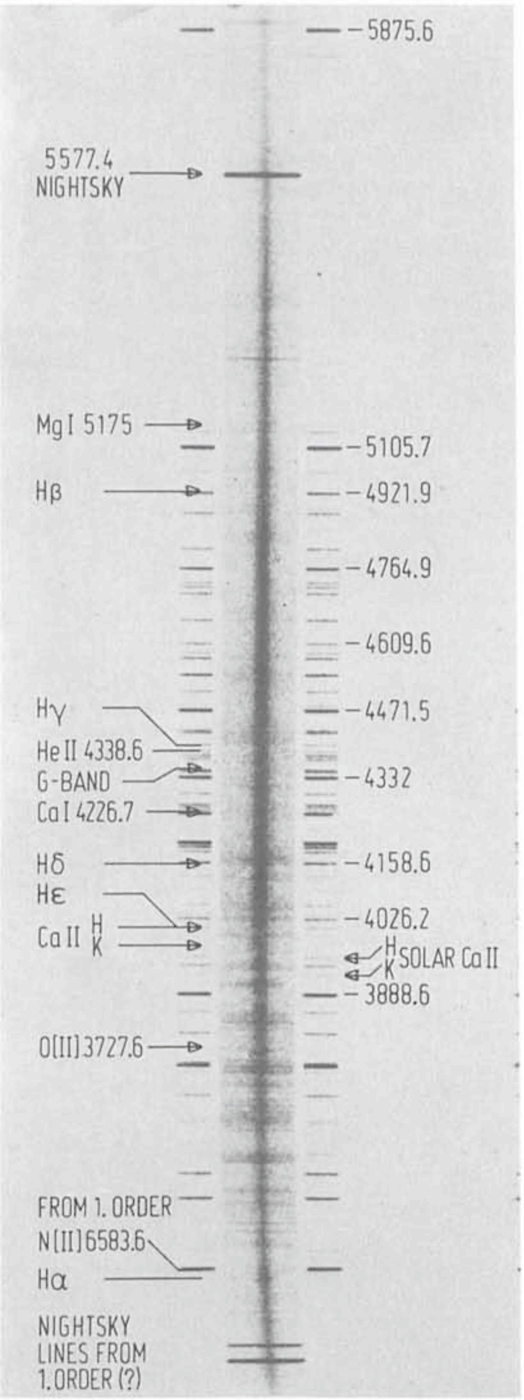

Fig. 4: *Spectrum of the edge-on Sb galaxy A1036.3–2818; exposure time 35 min., original dispersion 86 Å/mm. The position angle of the slit was set to the position angle of the galaxy. Note the inclination of the galaxy spectral lines – e.g. λ 3727 – along the slit. This gives a direct measure of the rotation of A 1036.3–2818.*

suggested that the cluster radial velocity dispersion, which represents a comparatively easily determined measure of the cluster gravitation potential, should be correlated with the cluster X-ray luminosity. On the basis of the X-ray observations the Hydra I cluster is at the low end of the diagram of X-ray luminosity versus velocity dispersion. Because no radio galaxy is known to exist in Hydra I, its X-rays cannot be due to a single active galaxy but must be generated by hot intergalactic gas. Also, the optical appearance of NGC 3312 suggests the existence of dispersed intergalactic matter. Fig. 2 shows the

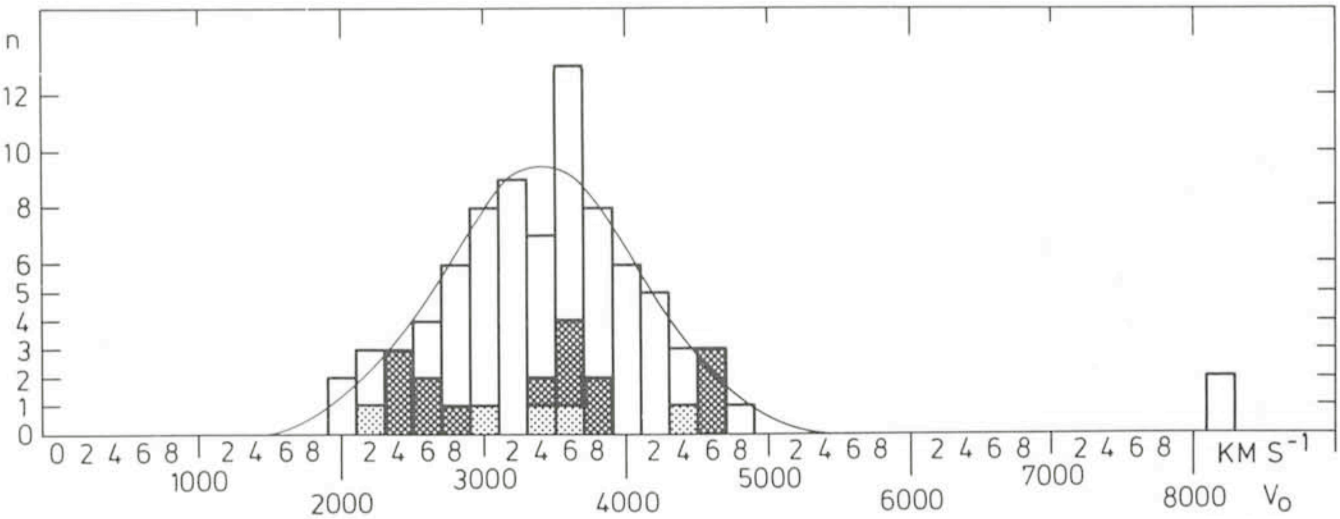

Fig. 5: *Histogram of radial velocities of galaxies in the Hydra I field; values from the literature are shaded. The overlap of the older sample and our own measurements is given in lighter shading. The Gaussian fit defines the mean radial velocity of the cluster and its velocity dispersion. Remarkable is the empty space in front and behind Hydra I (at least for $v_0 < 8,000$ km/s).*

bright disturbed spiral galaxy in the core of A1060, which has a linear extent of roughly 40 kpc. An asymmetrical distribution of very faint filamentary features has been detected in blue light extending from the disk of this galaxy to a projected distance of at least 30 kpc. Gallagher (1978, *Ap. J.*, **223**, 386) presented evidence that NGC 3312 is being stripped of its interstellar medium by ram pressure. Fig. 3 shows a contrast-enhanced image of NGC 3312, obtained by scanning the original 3.6 m PF plate with the PDS machine of the Lund Observatory and displaying the image on a TV screen using a logarithmic scale for the gray code.

The Hydra I Cluster: Observations

Accurate coordinates for more than 1,300 galaxies in the Hydra I field and magnitudes (to $0^{m}.2$) for a high percentage of them are available. Morphological types and radii are given for about 300 galaxies (R. J. Smyth, 1980, Thesis, ROE). In sharp contrast with this amount of data only 20 redshifts were known up to 1980. In order to derive more radial velocities we used the ESO 1.5 m telescope with the Boller & Chivens spectrograph equipped with an EMI 3-stage image tube during three observing periods in March 1980, May 1980 and April 1981. Spectra were recorded on photographic plates, which is a cheap but effective procedure. The Grant machine in Geneva was used to measure line positions accurate to about 0.5 μm. All spectra were taken with the same setting of the grating, i.e. the comparison spectrum is always the same. The difficult problem is to recognize and identify the lines in a galaxy spectrum, as they are often very faint and noisy. Furthermore, if only a few lines can be seen, it is difficult to identify them correctly. A sample spectrum is shown in Fig. 4. This way we were able to measure more than 100 radial velocities of galaxies brighter than about $15^{m}.5$, i.e. galaxies up to three magnitudes fainter than the brightest cluster member, and we reached the limit of the ESO 1.5 m telescope.

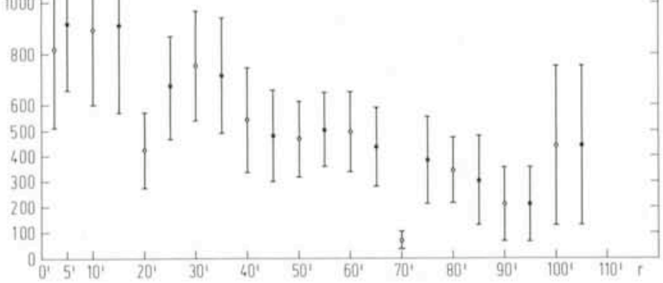

Fig. 6: Velocity dispersion within rings of 10′ width around the cluster centre. The data were sampled in two different ways (open and closed circles), where bins were shifted by 5′ relatively to each other.

The distribution of all radial velocities in the Hydra I field, presented as a histogram in Fig. 5, shows a very good definition of cluster membership in velocity space: there are no foreground galaxies in the observed field and no background up to 8,000 km/s. Such "holes" in space are also observed close to other superclusters. A Gaussian curve was fitted to the observed velocity distribution; the resulting mean radial velocity is $v_0 = 3,399 \pm 39$ km/s and the velocity dispersion is $\sigma = 684 \pm 38$ km/s which is comparable with the corresponding value for the Virgo cluster.

Further radial velocities of the same quality would not improve the accuracy of the mean radial velocity and the velocity dispersion significantly. But they would be of great help for computations of any three-dimensional dynamical model of this cluster as demonstrated in Fig. 6. As soon as we split up the total sample of radial velocities into subgroups to study the velocity dispersion as a function of distance from the cluster centre, a great number of individual measurements is needed. Owing to the rather small numbers of galaxies in some bins in Fig. 6, an improvement on the observational side is obviously necessary in order to perform smooth modelling. A further strong argument for carrying out observations with the ESO 3.6 m telescope is the fact that in the case of Hydra I, space in front and behind the cluster is quite empty. From the work of Smyth we learn that the Hydra I field still shows strong clustering at an apparent magnitude of $\sim 17^{m}.5$. Thus for this cluster we would be in the unique situation of being able to study the true luminosity function of its galaxies over a range of 6 magnitudes. To be sure of cluster membership this would clearly imply the need for radial velocities observed with the 3.6 m telescope.