Chapter 1

CLUSTER PROPERTIES

1.1 Introduction

Rich galaxy clusters are the largest bound systems in the universe (see, e.g., these reviews: Bahcall 1977b; Oegerle, Fitchett, & Danly 1990; Fabian 1991). In this chapter (§ 1.2 and § 1.3) I report general discussions about several cluster properties I have considered in my PhD thesis: richness, classification schemes, galactic content, density profiles and sizes, the optical luminosity function, characteristic times, masses and mass-to-light ratios. In § 1.4 X-ray emission and radio emission are also briefly discussed.

Section § 1.5 concerns recent studies on a recent interesting topic: the environmental effects on galaxies. It is well known that the frequency distribution of galaxy morphological types depends on the environment: ellipticals and lenticulars dominate the dense environments, such as the core of rich clusters, and spirals dominate the field. Several other correlations between galaxy properties and their environment are studied in the literature. In particular, I refer here to the very dense cluster environment. I also hint at some works of mine, not extensively discussed in this thesis (Girardi et al. 1991, Biviano et al. 1991, Girardi et al. 1992).

In the last section I briefly discuss how the large-scale structure in the universe can be traced by galaxy clusters.

CLUSTER POPULATIONS AND RICHNESS CLASSES			
Population	Class	Population	Class
30–49...........	0	130–199	3
50–79...........	1	200–299	4
80–129..........	2	300 or more ...	5

Table 1.1: From Abell 1958.

1.2 Static Properties

Richness

Richness is a measure of the number of member galaxies in a cluster within a certain distance from the cluster centre: it is thus also a measure of a mean number density in the cluster. The richness of clusters varies over a very wide range. Zwicky and his collaborators (Zwicky et al. 1961-1968) define and list cluster populations in their catalog, however these populations are distance dependent. Abell (1958) introduced a different and largely used distance-independent definition for the richness of a cluster: the Abell counts (or "population"), i.e. the number of galaxies within a fixed magnitude range (brighter than $m_3 + 2$, where m_3 is the photographic magnitude of the third brightest cluster member), and a fixed linear boundary, a circle of radius 1.5 $h^{-1}Mpc$. The Abell counts are corrected for the background. Abell also defined richness classes: clusters with a similar range of Abell counts belong to the same class (see Tab. 1.1). Among the other richness parameters used in the literature, there is the one by Bahcall (1977a): the number of galaxies brighter than m_3+2, inside a circle of 0.25 $h^{-1}Mpc$. Since this parameter concerns the very central part of clusters, Bahcall's richness is probably less contaminated by interlopers or by clusters superimposition than Abell's richness.

Classification Schemes

Clusters of galaxies can be organized into a one-parameter sequence analogous to galaxy Hubble type. A simple classification (e.g. Abell 1965) ranges from regular to intermediate to irregular-type clusters. The regular clusters are believed to be dynamically more evolved systems than the irregular

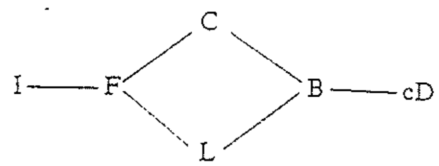


Figure 1.1: From Struble & Rood, 1982.

clusters. Common classification schemes are based on the following properties: the morphological appearance of the cluster (Zwicky, Rood-Sastry), the dominance of bright galaxies (Bautz-Morgan, Rood-Sastry), and the galactic content (Morgan, Oemler). I only discuss some of these.

Rood & Sastry (1971) based their detailed scheme on the distribution of the ten brightest members. The Rood-Sastry (RS) system (revised by Struble & Rood 1982) can be represented by the diagram in Fig. 1:1: The general classification criteria are as follows:

- cD-type: the cluster is dominated by a cD galaxy;
- B-type (=binary): the cluster is dominated by a bright binary system;
- L-type (=line): three or more of the ten brightest members are arranged in a line;
- C-type (=core): at least four of the ten brightest members are located with comparable separations in the cluster core;
- F-type (=flat): several of the brightest ten galaxies are distributed in a flattened configuration;
- I-type (=irregular): an irregular distribution of the galaxies with no well-defined centre.

Bautz & Morgan (1970) developed a classification system that depends on the relative luminosity contrast of the brightest galaxy to the other galaxies in each cluster. The Bautz-Morgan (BM) system distinguishes five cluster types:

- Type I: the cluster is dominated by a single, centrally located, cD galaxy;

	E	SO	S	(E+SO)/S	
cD Clusters:	35%	45%	20%	4.0	e.g. Coma, A2199
Spiral-poor:	15%	55%	30%	2.3	e.g. A194, A400, A539
Spiral-rich:	15%	35%	50%	1.0	e.g. Hercules, A1228, A1367, A2197
Field:	15%	25%	60%	0.7	e.g. de Vaucouleurs 1959, van den Bergh 1962, Faber & Gallagher 1976

Table 1.2: Galactic content of clusters (from Bahcall 1977b).

- Type II: the brightest members are intermediate in appearance between cD galaxies (which have extended envelopes) and normal giant ellipticals;
- Type III: the cluster contains no dominant galaxies;
- Type I-II and Type II-III are intermediate types.

A different type of classification scheme is based on the galactic content of galaxy cluster (Morgan 1962, Oemler 1974). Morgan (1962) classified clusters according to the morphological type of their bright members. More recently Oemler (1974) based his classification on cluster galaxy content:

- Spiral-rich clusters: their composition is similar to that of the field, with a high proportion of spiral galaxies;
- cD clusters: they are dominated by central supergiant galaxies and have no spirals in their cores. They contain a much higher proportion of ellipticals in the central regions than other cluster types;
- Spiral-poor clusters: they are intermediate between the previous types, with a composition dominated by S0 galaxies.

Galactic Content

Rich, dense clusters are dominated by elliptical galaxies; in the low-density general field spirals occur most frequently. Galaxies of type S0 are generally distributed in the same way as ellipticals. Tab. 1.2 reports the galactic content of some well-known clusters.

Further details about the galactic content for different environments are given in § 1.5.

Density Profiles and Cluster Sizes

The density profile of cluster galaxy-distribution can be described by a three-parameter function (if the cluster centre is fixed):

$$\rho(r) = \rho_0 f_1(r, r_c, r_h) \tag{1.1}$$

$$\sigma(r) = \sigma_0 f_2(r, r_c, r_h), \tag{1.2}$$

where $\rho(r)$ and $\sigma(r)$ are, respectively, the space and projected density profiles and f_1 and f_2 are functions that best fit the observed profiles. The three parameters are: the central density of galaxies per unit volume or area of the sky (ρ_0 or σ_0), a central scale length r_c, (e.g. the core radius), and the halo radius r_h that measures the maximum radial extent of the cluster. A number of models have been proposed to fit the galaxy distribution; the most commonly used profiles are the bounded isothermal function (Zwicky 1957, Bahcall 1972), the King function (King 1962), and the de Vaucouleurs function (de Vaucouleurs 1948).

The total size of a galaxy cluster is a matter of definition. Since the outer envelope of a cluster does not exhibit an obvious sharp edge, the size is not a uniquely defined property. Some of the scale lengths are directly obtained from the density profiles: the core radius R_c (defined as $\sigma(R_c) = \sigma_0/2$, from the isothermal or King profiles), the effective radius R_e (containing half the total galaxy number, from de the Vaucouleurs profile).

Some of the other more commonly used definitions include the following ones. The gravitational radius is defined as $R_G = \frac{2GM}{3\sigma_v^2} \sim 1.5\ h^{-1}Mpc$, where M is the cluster mass and σ_v is the observed velocity dispersion. R_G is the radius at which the gravitational energy approximately equals the kinetic energy of a galaxy moving in the cluster. The projected virial radius is defined as $R_V = D\frac{n^2}{\Sigma_{i<j} 2tan(r_{ij}/2)^{-1}}$, where D and n are the cluster distance and the number of galaxies in the cluster, respectively, and r_{ij} is the angular separation between galaxies. According to the standard virial theorem $M = \frac{3\pi}{2}\sigma_v^2 R_v/G$.

Density profiles and cluster sizes are more extensively discussed in chapter 5.

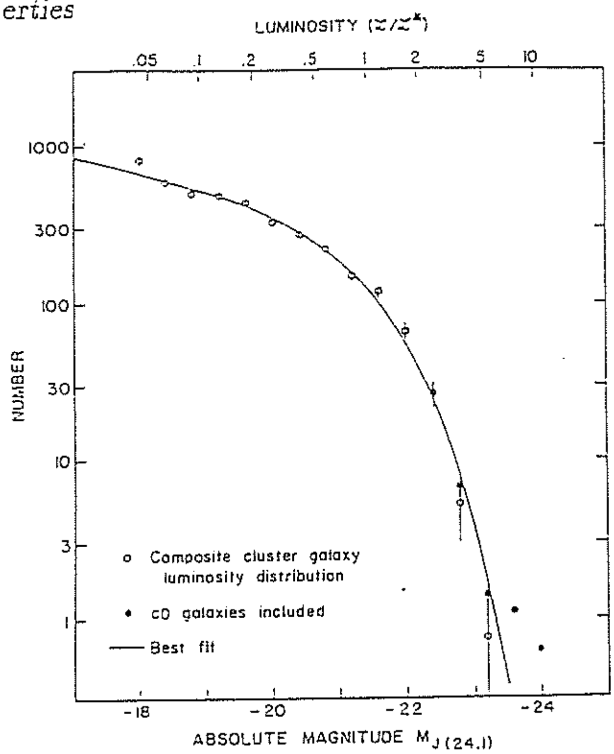


Figure 1.2: Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite (from Schechter 1976).

The Luminosity Function

The luminosity function of cluster galaxies is defined (in its integral form) as the number of galaxies $N(\leq m)$ brighter that magnitude m; this has been studied observationally by various investigators (see Binggeli, Sandage, & Tamman 1988 for a review paper). Several analytical representations for the cluster luminosity function have been proposed; I discuss only the largely used form of Schechter. Schechter (1976) suggested an analytic approximation for the luminosity function that shows good agreement with both the luminosity distribution of bright nearby galaxies and a composite luminosity distribution for cluster galaxies (see an example in Fig. 1.2).

The expression for the number of cluster galaxies in the luminosity interval L to $L + dL$, $N(L)dL$, is given by Schechter as

$$N(L)dL = N^*(L/L^*)^{-5/4} exp(-L/L^*)d(L/L^*), \tag{1.3}$$

where L^* is a characteristic luminosity (with an equivalent magnitude M^*) at which the luminosity function exhibits a rapid change in slope in the log$N$-log$L$ plane. The parameter N^* is proportional to the cluster luminosity and is a measure of its richness.

1.3 Dynamical Properties

Characteristic Times

In this subsection I discuss several characteristic time scales of galaxy clusters: the crossing time, T_{CR}; the two-body relaxation time, T_R; the dynamical friction time, T_{DF}; the collision time, T_{COLL}.

A galaxy travelling through a cluster with a velocity v will cross a radius R in a crossing time

$$T_{CR} = R/v \sim 3 \times 10^8 h^{-1}\ yr \times [(R/Mpc)/(\sigma_v/10^3 km\ s^{-1})], \tag{1.4}$$

where σ_v is the observed velocity dispersion. Galaxies at the outer regions of large superclusters (or perhaps even some clusters!) have crossing times greater than the Hubble time, and therefore have not yet had time to travel through the whole system.

The two body relaxation time for galaxies in clusters, which measures the time in which collisions can produce a large alteration in the original velocity distribution is given by (see Chandrasekhar 1942):

$$T_R = \frac{v^3}{4\pi G^2 M_g^2 N ln\Lambda} \tag{1.5}$$

$$\sim 10^{10} h^{-1}\ yr \times [(\sigma_v/10^3\ km\ s^{-1})^3/(M_g/10^{12} M_\odot)^2 (N/10^3\ gal\ Mpc^{-3}) ln\Lambda],$$

where v and M_g are the galaxy velocity and mass, N is the number density of galaxies in the cluster, and Λ is the ratio of maximum to minimum impact parameters. If relaxation is due to the dynamical friction of a galaxy moving through a homogenous and isotropic background distribution of lighter bodies, the term NM_g is replaced by ρ_{bg}, the background mass density in the cluster: thus $T_{DF} = v^3/(4\pi G^2 M_g \rho_{bg} ln\Lambda)$. Galaxies relax faster the larger their mass and the higher the environment density are in their vicinity. Some relaxation in cluster could have occurred in central regions for massive galaxies, no appreciable relaxation is expected for much lighter galaxies (see also chapter 4).

The average time between successive collisions of a galaxy with other members is given by

$$T_{COLL} = [2^{-1/2} v N \pi R_G^2]^{-1} \tag{1.6}$$
$$\sim 0.510^9 h^{-1} yr \times [(\sigma_v/10^3 km\ s^{-1})(N/10^3 gal Mpc^{-3})(R_g/10kpc)^2]^{-1}],$$

where R_g is the galaxy radius. Collisions may be important in the dense central region.

Masses and Dark Matter Distributions

Early estimates of cluster masses M were based on the standard virial theorem (see also Perea, del Olmo, & Moles 1990 for similar mass estimators):

$$M = \frac{3\pi}{2} \frac{< \sigma_v^2 > R_V}{G}, \tag{1.7}$$

where σ_v is the observed velocity dispersion and R_V is the projected virial radius, the brackets indicate spatial averages. These estimates yielded high values for the mass (i.e. $\sim 10^{15}\ M_\odot$ for the Coma cluster) and the mass-to-light ratio ($< M/L >\ 400 M_\odot/L_\odot$, see Bahcall 1977b). Since these dynamically determined masses are much higher than the conventionally estimated sum of the masses of the individual galaxies, large quantities of dark matter (hereafter DM, see e.g. Trimble 1987) are necessary. A fair estimate of cluster masses requires the knowledge of the DM distribution inside clusters. Merritt (1987) and other authors have shown that these estimates can be grossly wrong once one drops the assumption that light traces mass.

More recent estimates are based on the exact formulation of the virial theorem for a spherical system (e.g. Merritt 1987):

$$M = \frac{3 < \sigma_v^2 >}{< r^{-1} F(r) > G}, \tag{1.8}$$

where $F(r)$ is the fraction of the total mass of the system within radius r. Under the assumption that light traces mass, eq.(1.8) becomes the eq.(1.7). Unfortunately, the real distribution of matter in clusters, i.e. $F(r)$, is unknown.

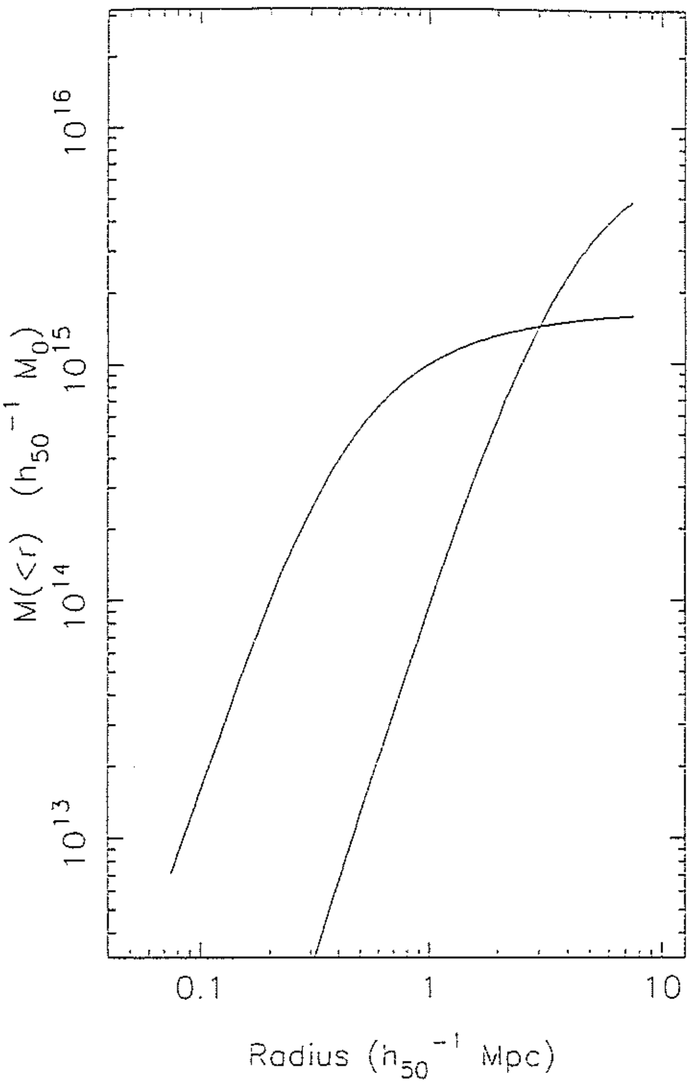
Moreover, the DM distribution in galaxy clusters can constrain the nature of DM itself (see e.g. Sciama, Persic, & Salucci 1992).

The determination of matter distribution in galaxy clusters via the study of optical data (that is positions and velocities of cluster galaxies) is based on the time-independent Jeans equation which is, assuming spherical symmetry and setting the mean-motion terms to zero (see e.g. Binney & Tremaine 1987):

$$n\frac{d\Phi}{dr} = n\frac{GM(r)}{r^2} = -\frac{n\sigma_r^2}{dr} - \frac{2n}{r}(\sigma_r^2 - \sigma_t^2), \tag{1.9}$$

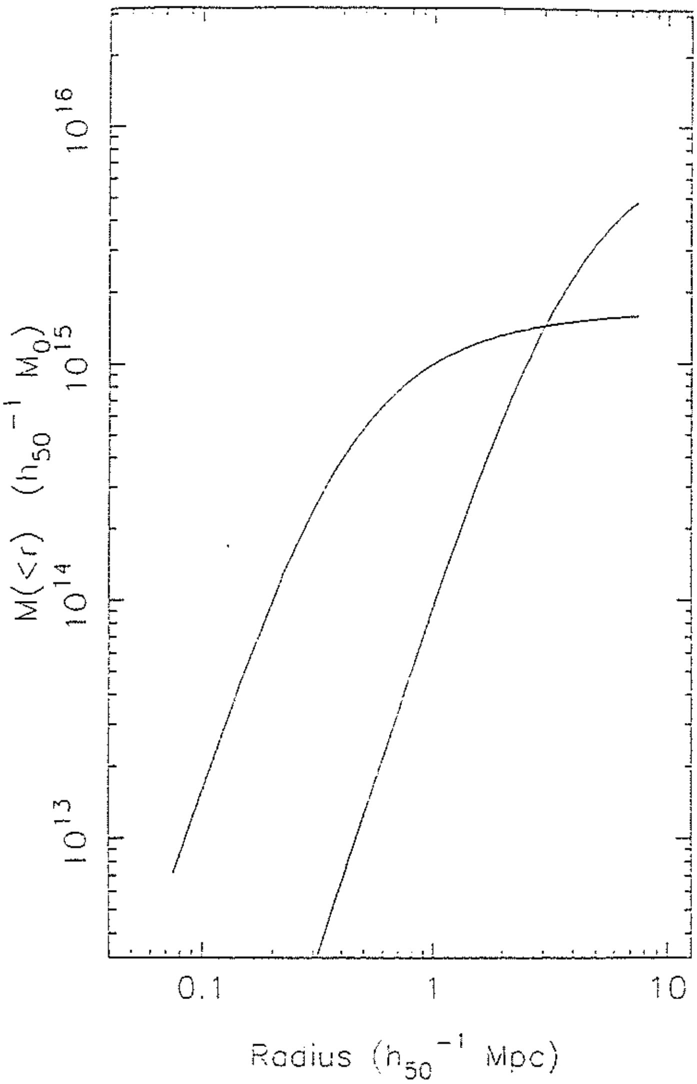
where $M(r)$ is the total mass contained within the radius r, $n(r)$ is the number density of some "tracer" population (e.g. galaxies) of the system, $\Phi(r)$ is the total potential, and σ_r and σ_t are the galaxy velocity dispersions along and tangential to any radius vector. Eq.(1.9) allows us to estimate the mass distribution in a cluster given knowledge of the three functions $n(r), \sigma_r(r), \sigma_t(r)$, or $n(r), \sigma_r(r), \beta(r)$ where $\beta(r) = 1 - \sigma_t(r)^2/\sigma_r(r)^2$.

Until recently, eq.(1.9) was rarely used for this purpose, primarily because of the difficulty of obtaining a usefully-large sample of galaxy radial velocities; this is no longer the case. By measuring the radial velocity of a large sample of galaxies, we can in principle determine $\sigma_v(R)$, the dependance of the line-of-sight velocity dispersion on (projected) radius from the cluster centre. But there is no way to deconvolve a single function of radius $\sigma_v(R)$ to obtain the two desired functions $\sigma_r(r), \sigma_t(r)$. Physically, this indetermination reflects the fact that spatial variations in either velocity anisotropy or cluster mass-to-light ratio may be responsible for the observed variation of σ_v with R. For the Coma cluster, Merritt (1987) showed that the velocity dispersion profile is consistent with several mass distribution: a fairly point like DM distribution with predominantly circular galaxy orbits near the cluster centre; a more diffuse DM distribution with predominantly radial orbits throughout the cluster; or the usual mass-traces-light model with isotropic orbits. The



The most extreme dynamically allowed dark matter distributions in the Coma cluster. The two curves correspond to the models discussed in the text. The curve which attains the highest mass corresponds to the most diffuse dark matter distribution compatible with the observations.

Figure 1.3: from Fitchett 1990.



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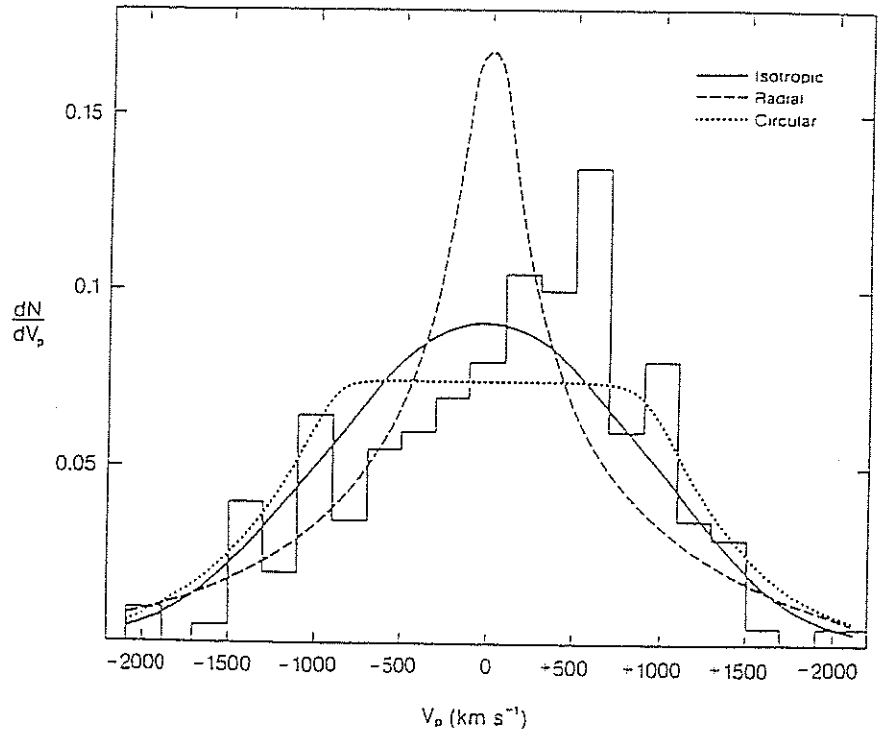

Figure 1.4: Distribution of line-of-sight velocity of galaxies in Coma. The histogram contains galaxies in the radial range $2R_c < R < 10R_c$ (where R_c is the core radius); the cluster mean is 6932 $km\ s^{-1}$. The three curves are the theoretical distributions derived from models in which the galaxy orbits are isotropic, completely radial, and completely circular; the dark matter distributions have been adjusted to give roughly the same velocity dispersion profile for each model. The curves have been convolved with a Gaussian of dispersion $= 100\ km\ s^{-1}$ to simulate velocity measurement errors (from Merritt 1987).

m_H is the proton mass and μ is the mean molecular weight. However, at present, the temperature profile has been obtained for only a few clusters.

Giant luminous arcs discovered in some high redshift clusters (e.g A370), if interpreted in terms of gravitational lensing, also give important constrains on mass and mass distribution in clusters. In the situation of a perfect Einstein ring (that is the ring produced by the perfect alignment of the "source", i.e. background galaxies, the "lens", i.e. the cluster, and the "observer") the total mass $M(b)$ interior to b (the arc impact parameter at the cluster) is:

$$\frac{M(b)}{\pi b^2} = \frac{c^2}{4\pi G}\left(\frac{D_{OS}}{D_{OL}D_{LS}}\right), \tag{1.11}$$

where the D_{ij} are angular diameter distances between the observer, lens and source. However, more realistic approaches are quite complex (e.g. Hammer & Rigaut 1989).

Up to now, estimates of mass via new techniques concern very few clusters, leading to a inhomogeneous outlook of clusters. Some evidence indicate that the DM is more centrally concentrated than the luminous mass in some clusters: e.g. Perseus (Eyles et al. 1991), A370 (Mellier et al. 1988a), CL2137-23 (Mellier, Fort & Kneib 1992); nevertheless the mass in Coma seem to be well traced by luminous matter (Watt et al. 1992). See also Fitchett (1990) for a recent review on this topic.

1.4 X-Ray and Radio Emissions

X-Ray Emission

The idea that extragalactic X-ray sources were generally associated with groups or clusters of galaxies was suggested by Cavaliere et al. (1971). The observations from satellite have established a number of properties of the X-ray sources associated with clusters (see Sarazin 1986,1988 for good reviews).

Clusters are the most common bright extragalactic X-ray sources. They are extremely luminous ($\sim 10^{43-45} ergs\ sec^{-1}$), with a wide range of luminosities, and their emission is not time variable. The X-ray sources associated with clusters are extended. Forman & Jones (1982) proposed a two dimensional classification scheme for the X-ray morphology of galaxies, which they relate to the evolutionary state of the cluster as determined by its optical properties. First, clusters are classified as being irregular (*early*) or regular (*evolved*); the second determinant is the presence or absence of a central, X-ray dominant galaxy in cluster.

It is well established that the emission mechanism is thermal bremsstrahlung from hot ($\sim 10^8 K$), low density ($\sim 10^{-3} atoms/cm^3$) intracluster gas (although particularly strong X-ray emitting galaxies may contribute). The total mass of hot gas in a typical cluster is similar to the total mass of all galaxies in the cluster. This intracluster gas fills the space between the galaxies and the density can be fairly accurately determined from the surface brightness profile. If the galaxy distribution is well described by a King's density profile, the surface brightness as a function of projected radius r is (see also § 5.2):

$$S(r) \propto [1 + (\frac{r}{r_c})^2]^{-3\beta+1/2}, \tag{1.12}$$

where r_c is the cluster core radius and β is the ratio of kinetic energy/unit mass in galaxies to kinetic energy/unit mass in gas. Jones & Forman (1984) found that $\beta < 1$ implying that more energy is in the gas than in the galaxies of the system; however, there is not a complete agreement on the question (e.g. Ulmer 1988, Edge & Stewart 1991).

The X-ray spectra of clusters show strong X-ray line emission from iron and other heavy elements; this indicates that a significant portion of the intracluster gas must have been ejected from galaxies in the cluster. However, since the intracluster gas mass is so high respect to stars, a fraction of the gas must be primordial.

Considerable evidence has accumulated that the hot X-ray emitting gas is cooling in some clusters and it is being accreted onto large, central galaxies; the phenomenon is known as "cooling flows" (see Fabian 1988, 1991). This may be a possible explanation for the creation or accretion of the cD galaxies in some clusters.

Radio Emission

The associations between radio sources and clusters of galaxies was first made by Mills (1960). The radio emission from clusters of galaxies is synchrotron emission due to the interaction of a nonthermal population of relativistic electrons (with a power-law energy distribution) with a magnetic field. The radio emission from clusters is mainly due to sources associated with individual radio galaxies. This appears to be mainly due to the fact that strong radio emission is primarily associated with giant elliptical galaxies, which occur preferentially in clusters. A correlation seems to exist between cluster radio emission and cluster morphology (Owen 1975), but not with cluster richness. Some possible correlation with X-luminosity is also discussed (Sarazin 1986). See Sarazin (1986,1988) for reviews.

1.5 Clusters as Rich Galaxy-Environments

Rich clusters of galaxies are known to be very dense galaxy environments (hundreds of galaxies in a region about $1h^{-1}Mpc$ in size). Moreover, the presence of a non negligible intergalactic medium must be considered. The X-ray emission from many rich clusters (see § 1.4) reveals the presence of large quantities of hot gas. The presence of dust is still debated (see Girardi et al. 1992 for dust in galaxy groups, and reference therein for dust in clusters). Several processes may operate in such rich environments (see White 1982, Richstone 1988 for reviews): two-body relaxation and dynamical friction, collisional stripping and stripping from the mean cluster field, truncated star formation, ram-pressure. All these processes (and/or particular initial conditions) are invoked to explain the observational findings I am going to discuss.

Morphological Segregation

For many years (e.g. Hubble & Humason 1931), astronomers have known that for a given sample of galaxies the frequency distribution of Hubble types depends on the environment from which the sample is selected: elliptical and S0 galaxies are the dominant population in the densest region of rich clusters, whereas spirals are most frequently found in settings of much lower density. The dependence of morphological fractions of galaxies on environment is very well established fact. Dressler (1980b) demonstrated that this correlation also holds inside rich clusters. Dressler concluded that the fundamental

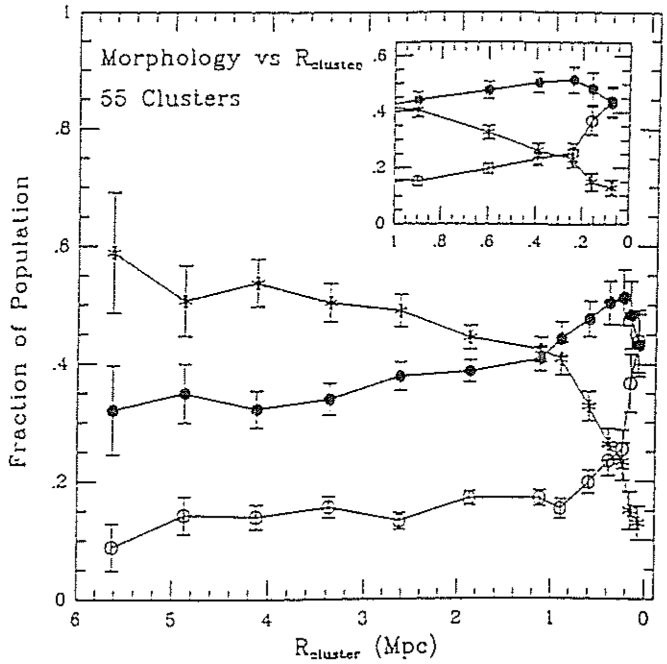

Figure 1.5: The fraction of E (open circles), S0 (full circles), and S+I (stars) galaxies as a function of the clustercentric distance for 55 clusters. The insert in the upper right shows the same data at higher spatial resolution. (from Whitmore & Gilmore 1991).

correlation is between morphological type and *local* projected galaxy density. Moreover, this correlation does not seem to depend on the cluster concentration. According to the previous *localist* interpretation, galaxy morphology in rich clusters is determined by the characteristics of clumps, in which galaxies would lie, rather than by the properties of the virialized largest scale structure. Salvador-Sole', Sanroma', & Jordana (1989) have proposed an alternative explanation (*non localist*) of the observed relation (morphological fraction versus local projected number density in rich clusters). The relation appears to be linked to the properties of the largest scale virialized structures where galaxies reside. Whitmore & Gilmore (1991) supported this interpretation while claiming that the galactic morphology slightly better correlates with the cluster-centre distance than with the local density (see Fig. 1.5).

Several possible explanations of the morphological segregation effect are discussed in the literature, but there is not complete agreement. Models are based on galaxy evolution and/or initial conditions (e.g. Dressler 1984;

Postman & Geller 1984).

There is also some evidence for the morphological segregation in velocity space: late type galaxies move faster than early type galaxies (e.g. Moss & Dickens 1977). A more detailed explanation of this phenomenon is reported in § 4.4.1, where I also describe the results of a research of mine.

The appearance of spiral arms (the arm-class parameter is defined by Elmegreen & Elmegreen 1982) may also depend on environment. Elmegreen & Elmegreen (1982, 1987) found that *grand-design* galaxies prefer poor environments; but Giuricin, Mardirossian, & Mezzetti (1989) found that *flocculent* type is more common in interacting and binary galaxies. The large number of *gran-design* galaxies in denser environments could be explained by the connection between the appearance of spiral arms and the disk-mass to halo-mass ratio (Elmegreen & Elmegreen 1990). Evidences for this connection were simultaneously found by Elmegreen & Elmegreen (1990) and by Biviano et al. (1991). In this paper (Biviano et al. 1991) I found that arm classes correlate with the velocity gradients of rotation curves: galaxies with flatter curves tend to have a grand design morphology, and galaxies with steeper curves tend to have a flocculent arm structure. If gradients are fair indicators of disk-to-total mass ratios (Persic & Salucci 1988), grand design morphologies are favoured by an "important" disk.

Size and Luminosity

One of the best indications that the cluster environment can affect the structure of galaxies is the existence of cD galaxies near the centres of many clusters (cD galaxies are giant elliptical galaxies with extended amorphous halos). They are observed to reside in regions where the local density is high. It is unlikely that cD galaxies coincide with statistical fluctuations of galaxy luminosity-function (e.g. Schechter 1976). In order to explain cD formation several models were proposed According to the *weak* cannibalism hypothesis (Ostriker & Tremaine 1975), a massive galaxy which happens to lie near the centre of a cluster will undergo a significant, although modest, increase in luminosity over a Hubble time as it accretes less massive neighbors and bound satellites. According to the *strong* cannibalism hypothesis (White 1976a, Hausman & Ostriker 1978), orbital decay and merger times are sufficiently short that a superluminous galaxy will naturally form at the centre of any rich relaxed cluster after about 10^{10} years. The cooling of hot X-ray emitting gas in cluster cores (*cooling flows* have been invoked to explain the formation/evolution of cD galaxies (Mushotzky et al. 1981).

In general, it has been claimed that galaxies of higher luminosity may slightly prefer denser environments (e.g., Binggeli 1987). As a matter of fact, bright galaxies in clusters appear to be brighter than non-cluster bright galaxies (e.g., Iovino et al., 1990) and the absolute magnitudes of the brightest (relatively) isolated galaxies turn out to be, on average, one magnitude fainter than those of the clustered brightest galaxies (Einasto & Einasto, 1987). Lugger (1989) found that in higher density region there is an excess of very bright galaxies and the luminosity function is flatter. However, Binggeli, Sandage, & Tammann (1988) found that overall galaxy luminosity function is substantially independent of the environment and they suggested that eventual differences can be explained in term of a different proportion of morphological types. This luminosity segregation may be due to particular initial conditions in the LSS formation; instead the process of dynamical friction may be particularly important for the segregation inside clusters. The luminosity segregation in galaxy clusters is also described in chapter 4.

As far as the galaxy size is concerned, several physical processes can effect the galaxy structure: collisional stripping due to galaxy-galaxy interaction; tidal truncation due to galaxy-cluster interaction, merging phenomenon (see White 1982 for a review). Some photometric studies on galaxies in dense environments show that they have either distended (see e.g. Kormendy 1977) or truncated luminosity profiles (e.g. Schombert 1987; Lauer 1988). Numerical simulations by Anguilar & White (1986) showed that different kinds of encounters galaxy-galaxy can cause different changing in galaxy luminosity-profiles (distending or truncating). Moreover, Baggett & Anderson (1992) suggested that local environment may be more important than global environment: they found that galaxies with near neighbours have systematically larger slopes in their disk brightness and color profiles.

The detailed studies of luminosity profiles are possible for "few" galaxies; on the contrary, measures of integral luminosity and size exist for larger samples of galaxies. The comparison of galaxy size for a fixed luminosity may be useful. For instance, Strom & Strom (1978a,b,c) and Peterson, Strom & Strom (e.g. 1979) found that the radii of galaxies in rich environments are smaller at a given M_V than the corresponding radii in poor environments. This luminosity-diameter relation is so tight it seems a very suitable tool to study the influence of the environment on galaxies. In recent papers.

Giuricin et al. (1989) and Girardi et al. (1991) analysed the luminosity-diameter relation. In the last one, I examined the relations between the blue total corrected absolute magnitude and the absolute corrected isophotal diameter for galaxies in very different environments. I found no evidence of environmental dependence, especially if selection criteria relative to the various samples are taken into account.

Interstellar Gas Content of Cluster Galaxies

As far as the neutral hydrogen in disk systems is concerned, it is well established the presence of the *anaemic spirals* (van den Bergh 1976) in clusters (Strom & Strom 1979; Wilkerson 1980; Sullivan et al. 1981; Bothun et al. 1982; Warmels Cayatte et al. 1990, see Haynes, Giovanelli, & Chincarini 1984 for a review). These observations show that in the intermediate-density environments (there are very few spirals in the densest environments) spirals tend to be gas poor by factors of 2-3 relative to their field counterparts of the same Hubble type; S0 show a similar tendency (Krumm & Salpeter, 1979a,b). In an evolved cluster, like the Coma cluster, all the disk galaxies near the cluster centre show a very low gas content (Sullivan et al. 1981). Fig. 1.6 shows the HI-deficiency histograms for nine clusters: more HI-deficient galaxies are the more centrally located galaxies.

For the Virgo cluster a differential study is also possible: in the innermost region the galaxies are HI deficient by a factor of 2 to 5, and occasionally, up to 10 (Chamaraux et al. 1980). Moreover, the HI distribution in galaxies may deviate from circular symmetry (e.g. Bosma 1881, Dickey & Gavazzi 1991).

There exist several theoretical mechanisms efficient enough to remove gas from spirals in rich clusters: ram-pressure stripping (Gunn & Gott 1972; Gisler 1978,1979), thermal-evaporation (Cowie & Songalia 1977; Balbus & McKee 1982) or tidal stripping (Larson et al. 1980). It is also possible that the observed, present-day HI deficiency in cluster spirals is the result of an initial defect and that cluster galaxies are simply endowed with less post-formation residual gas than field galaxies.

However, neither ionized gas nor molecular gas, identified by CO emission, are significantly affected by environment (Stauffer 1983; Kenney & Young 1989).

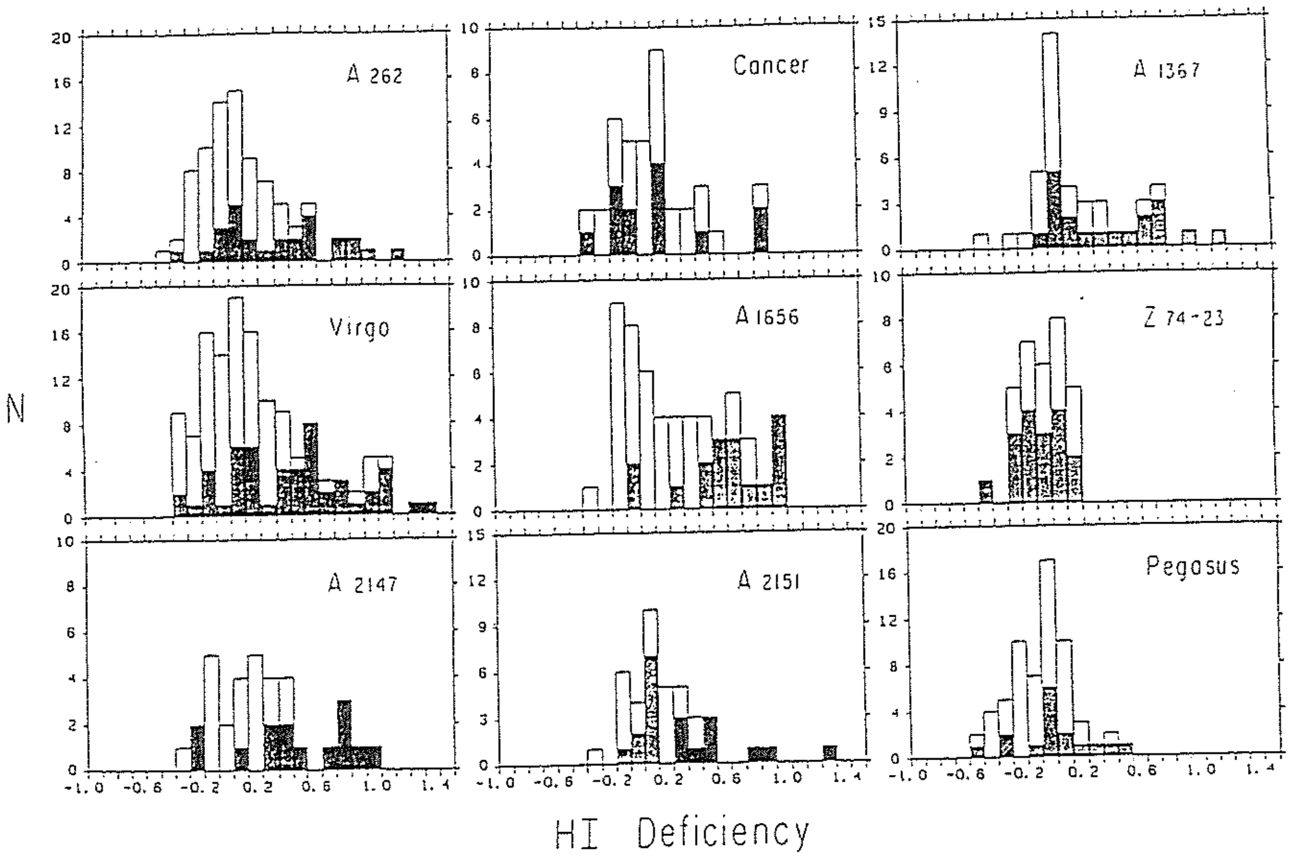

Figure 1.6: Histograms of H I deficiency in nine clusters. The upper envelope represents all galaxies in each cluster sample; the shaded one, those projected within one Abell radius from the center (from Haynes, Giovanelli, & Chincarini 1984).

Galaxy Activity

The fact that spirals in Virgo are redder than their field countparts has been known since the work by Holmberg (1958). After a large debate in the literature (see e.g. Visvnathan & Sandage 1977), the final results seem to be that the Virgo galaxies are actually redder that field galaxies (Kennicutt 1983), but their colours are normal relative to field galaxies with the same HI content (Stauffer 1983). A possible explanation is that a deficiency of gas would depress the star formation rate, and hence the $H\alpha$ emission, and would in turn gradually act to redder the integrated colours of the galactic disks (Searle, Sargent & Bagnuolo 1973).

Several studies concern the relation between environment and stellar-formation activity (*star formation rate*, SFR). There are several indicators of star formation: the equivalent width of $H\alpha$ (Kennicutt & Kent 1983), related to HII regions (Cohen 1976); the far infrared (FIR) emission from galaxies, interpreted as radiation emitted by dust heated by the stellar photon field; the radio continuum. The effect of environment on these indicators is controversial, even if there is some evidence that the gaseous and stellar content of galaxies may be altered.

The galaxy emission-line equivalent width $H\alpha$+[NII] seems to be weaker in the Virgo cluster than in the field (Kennicutt 1983). On the contrary some authors (Moss 1988, Pesce 1991) found that normal emission, most likely due to star formation, is enhanced in early type cluster spirals when compared to similar spirals in the field. There is a debate on FIR/optical luminosity functions of galaxies in different environments (Gavazzi, Boselli & Scodeggio, 1990; Sulentic, 1990). Some evidence was found that spiral galaxies in clusters have their radio emission (per unit visible light) enhanced with respect to isolated galaxies (e.g. Gavazzi & Jaffe, 1986; Gavazzi, Boselli & Scodeggio, 1990).

The phenomenon of AGN's (*active galactic nuclei*) seems to be connected to its environment (e.g. Heckman 1990). The environment immediately nearby the host galaxy is found to affect the AGN's more than global environment: e.g. host galaxies of QSO's (*quasi stellar objects*) show evidence of interactions (Heckman 1990 and references therein). See e.g. Balick & Heckman (1982), and de Vaucouleurs (1991) for discussions about the effects of cluster environment on AGN's.

Rotation Curves

Recent observations allow us to discuss the effect of environment on the rotation curves for spiral galaxies also differ in different environments. Several papers have addressed this issue with contradictory results (Rubin 1983, Chincarini & de Souza 1985, Burstein et al. 1986). The correlation between the outer velocity gradient and environment was found to be good by Whitmore et al. (1988), but it was not confirmed in recent studies (Balkowski 1990).

The Tully-Fisher and $D_n - \sigma$ Relations

The two principal methods for predicting the distances of more distant galaxies, namely the Tully-Fisher relation for spiral galaxies (Tully & Fisher 1977) and the $D_n - \sigma$ relation for early-type galaxies (see Burstein et al. 1987), both rely on the existence of a physical relationship between two galaxy properties: a luminosity-dependent quantity (total luminosity or diameter) and dynamical quantity (rotation velocity or central velocity dispersion). Yet each of these parameters might be related to their environment in ways that are still poorly understood.

Some authors claim that there is no environment evidence (Bothun et al. 1984; Richter & Huchtmeier 1984; Giuricin, Mardirossian & Mezzetti 1986; Biviano et al. 1990; Burstein 1990), others claim the opposite (e.g. Roberts 1978); Rubin et al. 1985; Djorgovski, De Carvalho & Han 1989).

The eventual absence of environmental dependence leads one to a picture of galaxy formation in which the formation process is heavily influenced by the environment of the galaxy (see morphology and HI content), while the internal workings of a galaxy, once formed, are dictated more by the gravitational field of the galaxy than by external influences (Burstein 1990). However these relations may depend on other parameters. Persic & Salucci (1991) showed that the curvature term in the Tully-Fisher relation arises as an effect of the systematic variation of DM abundance with luminosity in spiral galaxies.

Galaxy Alignment

The evidence of an eventual galaxy alignment can be fundamental in constraining the formation of large-scale structure. If clusters are formed by fragmentation of larger structures, according to the dissipative pancake scenario, one expects some sort of correlation between the orientation of a cluster galaxy and the orientation of its parent pancake (see e.g. Doroshkevich, 1970).

Unfortunately, there is a long controversy about observations of anisotropy in the orientations of galaxies. Some evidence supports the galaxy alignment (e.g. Thompson 1976; Dressler 1976; Gregory, Thompson, & Tifft 1981; Fong, Stevenson & Shanks 1990), but other researches gave null results (Helou & Salpeter 1982; McGillivray et al. 1982; Kaprandis & Sullivan 1983; Flin & Godlowski 1984).

Some authors also suggested that major axes of clusters show the same in the same supercluster show the same orientation as their "parent" supercluster (West 1989 and references therein).

1.6 Clusters and the Large-Scale Structure

Galaxy clusters are also interesting as tracers of large-scale structure. The study of large-scale structure is an attempt to understanding how matter, or at least luminous matter (galaxies, and galaxy clusters) are distributed in space. Since large structures evolve very slowly with time [1], large structures observed today are cosmic fossils of conditions that existed in the early Universe. A recent method of investigating structure in the Universe is using the high-density peaks of the galaxy distribution, i.e. the rich clusters of galaxies, as tracers of the large scale structure. I briefly describe here some results, referring the reader to Bahcall (1988), and Chincarini, Guzzo, Scaramella, Vettolani, & Iovino (1991) for reviews on this topic.

Abell (1958) was the first to notice that rich clusters of galaxies were themselves clustered into larger structures (superclusters). Superclusters are very large unvirialized systems ($\sim$ 100 Mpc), irregular in shape, with no well-defined boundaries. The spatial distribution of rich clusters and the clustering properties of clusters have been the subject of considerable interest in the literature.

[1] Even for typical velocities of $\sim 10^3$ km/s, objects can move only $\sim 10\ h^{-1} Mpc$ within the Hubble time

A significant step forward in the study of the very largest structures was made by Bahcall & Soneira (1983). By considering 104 nearby Abell clusters with known redshifts, they found that galaxy clusters clump even more strongly than galaxies, and claimed a measurable amplitude for the spatial correlation function [2] out to $\sim 150\ h^{-1}Mpc$. On a similar scale, there is the existence of a "bulk motion" with a speed of ~600 km/s relative to the microwave background of the sphere of galaxies and clusters around us within $\sim 30\ h^{-1}Mpc$ (e.g. Aaronson & Mould 1988).

Bahcall & Soneira (1982) studied the large void of galaxies in Bootes, and found that the largest, densest superclusters are located near and around areas devoid of galaxies. Previous observational evidence (see e.g. Gregory, Thompson, & Tifft 1981; Chincarini, Rood, & Thompson 1981), as well as more recent redshift survey (e.g. da Costa et al. 1988), indeed suggest that galaxy voids may be generally associated with surrounding galaxy excesses.

In the future, automated deep survey of galaxy clusters, including complete samples of X-ray clusters, will be useful in order to trace the largest scale structures.

[2] the spatial correlation function $\xi(r)$ is defined by the joint probability $dP(r)$ of finding two objects separated by a distance r and within volume elements dV_1 and dV_2, such that $dP(r) = n^2[1 + \xi(r)]dV_1 dV_2$, where n is the space density of objects in the sample.