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CLUSTER EVOLUTION

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CLUSTER EVOLUTION

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The galaxy and cluster luminosity functions are constructed from a model of the mass distribution based on hierarchical clustering at an epoch where the matter distribution is non-linear. These luminosity functions are seen to reproduce the present distribution of objects as can be inferred from the observations. They can be used to deduce the redshift dependence of the cluster distribution and to extrapolate the observations towards the past. The predicted evolution of the cluster distribution is quite strong, although somewhat less rapid than predicted by the linear theory.

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The galaxy as well as the cluster luminosity functions are fairly well determined by the observations (Abell 1958, Schechter 1976, Bahcall 1979, Sandage et al 1987), at least for the present epoch. The evolution of the mass and size of these clustered objects, even in the recent past, is on the other hand totally unknown. A recent theoretical progress (Schaeffer 1985, 1987) however allows the construction of these luminosity functions from the matter (or galaxy) correlations. The prediction is that the calculated luminosity function is quite similar, for both the galaxies and the clusters, to the phenomenological parameterisation introduced by Schechter (1976) :

$$\rho(L)dL \sim (L/L_*)^{\alpha}\, e^{-L/L_*}\, dL \tag{1}$$

The theory, however, shows that L_* is proportional to the luminosity density and to the two-body correlation function

$$\xi(r) \sim (r/r_0)^{-\gamma}, \quad r_0 \sim 5h^{-1}\mathrm{Mpc}\ , \quad \gamma \sim 1.8 \tag{2}$$

for a cluster of size r. It can thus predict (Schaeffer and Silk 1987) the time, that is the redshift dependence of the typical luminosity of a cluster, and whence the redshift dependence of the cluster distribution.

To construct the cluster luminosity function, we start from the obvious consequence of hierarchical clustering, namely that the matter distribution is scale invariant. If the two-body correlation function behaves, eq.(2), as $r^{-\gamma}$, the three-body correlation function is expected to vary as $r^{-2\gamma}$, and the N-body correlations as $r^{-(N-1)\gamma}$. A convenient parameterisation of this N-body correlation function is thus (Fry 1984, Schaeffer 1984)

$$\eta_n(r_1 \ldots r_N) = Q_N \sum \prod^{N-1} \xi(r_{ij}) \tag{3}$$

where $\prod^{N-1}$ denotes the product of N-1 two-body correlations functions depending on different relative coordinates $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ and Σ is the sum over all possible such products (see the previously quoted papers for more details). The coefficient Q_N is a parameter that is arbitrary. The parameter set $\{Q_N\}$, which is infinite, determines the matter distribution and represents the remaining freedom after hierarchical clustering is assumed. From these correlation functions, all statistical properties of the matter distribution can be calculated : the probability of holes (White 1979, Sharp 1981, Fry 1984, Schaeffer 1984), the cluster distribution as well as the cluster correlations (Schaeffer 1985, 1987). A convenient parametrisation that is seen to reproduce all these observations is (Schaeffer 1984, 1985)

$$Q_N \sim \frac{\lambda^N}{N^\nu} \quad , \qquad \text{with } \lambda = 2^\nu, \quad \nu = 1 \pm 1 \tag{4}$$

Other models where the coefficient Q_N decreases much more rapidly with N,

$$Q_N \propto N^{-N} \tag{5}$$

have been proposed (Fry 1984) and do as well in reproducing the observed distribution of holes and cluster correlation function, but predict considerably less large clusters since with the choice (5) the distribution of the latter decreases as $\left(\frac{L}{L_*}\right)^{-L/L_*}$ rather than as e^{-L/L_*}. We thus use the model (4) for Q_N to calculate the cluster (and galaxy) luminosity function. The result has been derived in (Schaeffer 1987). With some simplification it basically reads

$$\rho(L)dL \approx \rho_0 \left(\frac{L}{L_*}\right)^{-1} [\ell n(1 + L_*/L)]^{\nu+2} \; e^{-L/L_*} \; dL \tag{6}$$

which is nearly the form (1), the Schechter power law $\left(\frac{L}{L_*}\right)^{-1.2}$ being replaced by $\left(\frac{L}{L_*}\right)^{-1}$ times a logarithmic divergence $(\ell n \; L_*/L)^{\nu+2}$ that has the same effect than the additional factor $\left(\frac{L}{L_*}\right)^{-0.2}$ in the phenomenological parameterisation. The typical luminosity L_* is given by

$$L_* = a \, \rho_L \, \xi(R) V \tag{7}$$

where ρ_L is the luminosity density in the universe, R the cluster radius, V its volume and $a \sim 14 \times 2^\nu$ is a numerical constant. More precise forms can be obtained and are seen to match the observations for $\nu = 1$ (Fig. 1 and 2), which is the value that also reproduces the observed probability of holes.

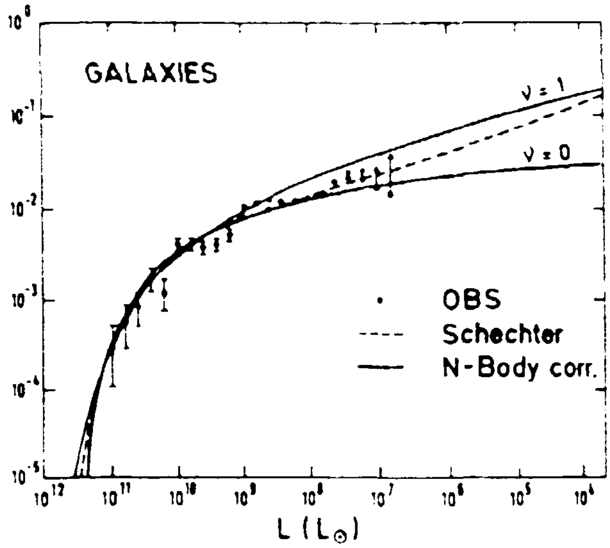

Fig. 1 : Galaxy luminosity function (Schaeffer 1987). The full lines are the predictions of the hierarchical clustering model for the non-linear matter distrbution, with various values of the parameter ν (eq. 4). The data are from Sandage et al (1987) and have been normalized to a Schechter type curve (dashed line) with parameters taken from Bahcall (1979)

The evolution of the cluster distribution may be inferred (Schaeffer and Silk, 1987) since expression (7) can provide for the redshift dependence of L_* and whence of $\rho(L)$. We concentrate on virialised clusters. Cluster evolution is expected to have occurred fairly recently, at an epoch where the galaxy evolution was mild. We thus expect the luminosity density simply to be scaled by the expansion :

$$\rho_L \propto (1 + z)^3 \rho_L^{(0)} \quad (8)$$

The correlation function, at the scales where clustering is important, follows the virialized solution of Peebles (1980)

$$\xi\left(\frac{r}{1+z}, z\right) \sim (1+z)^{\gamma - 3} \xi(r,0) \quad (9)$$

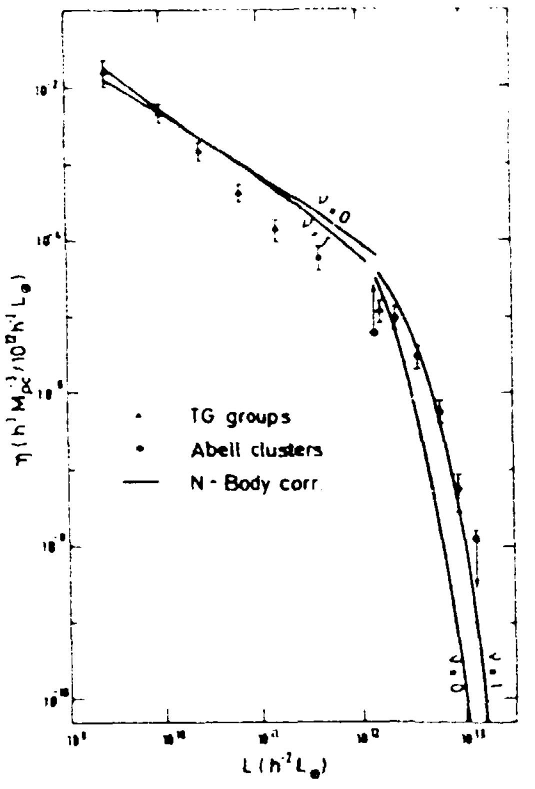

Fig. 2 : Cluster lumosity function (Schaeffer 1987). The full linees are the predictions of the hierarchical clustering model for the non-linear matter distribution, with various values of the parameter ν (eq. 4). The data result from a compilation by Bahcall (1979) of the luminosity distribution of Turner-Gott groups and Abell clusters

This behaviour is expected to hold up to the redshift where the scale considered gets non-linear. Then, from the virialization condition for a cluster of radius R

$$R < \left(\frac{L}{L_v}\right)^{1/3} \frac{1}{1+z} \, h^{-1} \text{ Mpc} \tag{10}$$

with $L_v \sim 2.5\ 10'' \ h^{-2}\ L_\odot$ we get the cluster luminosity distribution

$$\begin{aligned} \rho(L)dL &\sim \rho_0 \ x^{-1} \ [\ell n(1+x)]^{\nu+2} \ e^{-x} \ dL \\ x &= 0.4 \ (1+z)^{3-\gamma} \left(\frac{L}{L_v}\right)^{\gamma/3} \end{aligned} \tag{11}$$

that is plotted in Fig. 3. It shows a considerable spread in luminosities, with a large number of small objects of low luminosity. At large luminosities there is an exponential cut at a typical luminosity

$$L_* \sim 1.2\ 10^{12}\ (1+z)^{-3(3-\gamma)/\gamma}\ h^{-3}\ L_\odot \tag{12}$$

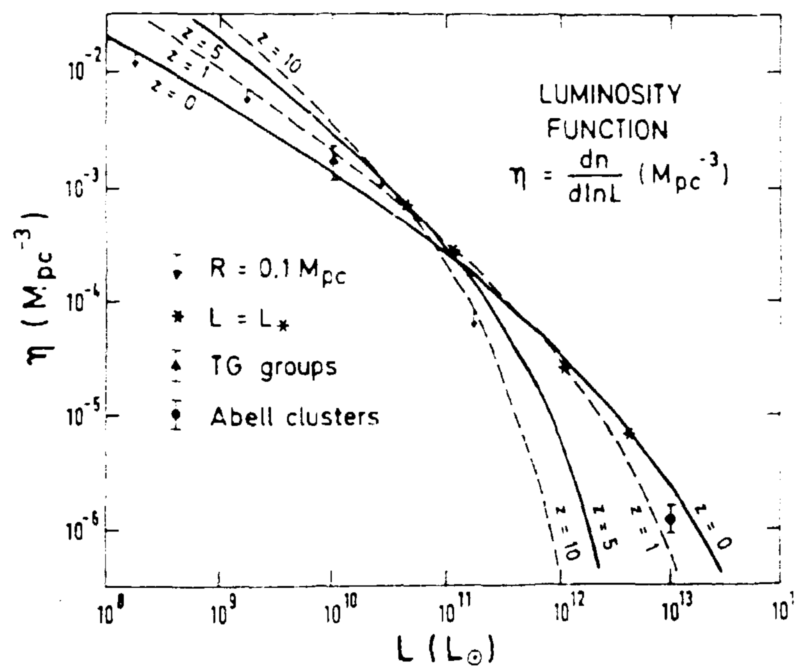

Fig. 3 : Luminosity distribution of virialized clusters (Schaeffer and Silk 1987). The differential number density $\eta = \dfrac{d\ N_{cl}}{d\ \ell n\ M}$ of all virialized clusters is given as a function of luminosity, for various redshifts. Note the large number of low luminosity clusters. Their average size R diminishes with decreasing luminosity. The arrow indicates the place where R is equal to 0.1 Mpc.The number of small clusters increases with redshift, reflecting the decrease of their average typical luminosity L_* Eq.(12) and size (Eq. 13). The sudden disappearance of all clusters is expected at the redshift where the considered scales from non-linear to linear behaviour.

This is a fairly strong evolution since $L_* \propto (1+z)^{-2}$, that despite the large spreading of L, might be measurable. A typical cluster has a radius

$$R_{cl} \sim 1.7\ (1+z)^{-3/\gamma}\ h^{-1}\ \mathrm{Mpc} \tag{13}$$

and a virial temperature

$$T_{cl} \sim 1.8\ 10^{7}\ (1+z)^{-3(2-\gamma)/\gamma}\ \mathrm{K} \tag{14}$$

which is nearly constant as a function of redshift. These scaling formulae for typical cluster are similar to the ones derived from linear theory by Kaiser (1986). They, however, are based on the non-linear distribution of matter and thus specifically apply to the virialized clusters at times close to the present epoch that we are studying. Eq. (11) shows also the large dispersion of luminosity (and thus sizes and temperatures), and our scaling, eq.(7) can be used to infer the whole luminosity distribution.

The knowledge of the cluster luminosity function at non-zero redshift has much wider applications than just the study of the cluster distribution. Having no adjustable parameter, the theory is predictive and can be used to calculate the X-ray background or the fluctuations of the microwave background induced by the Sunyaev-Zeldovich effect. The evolution of galaxies may be studied in the same way, provided on has some control of their intrinsic luminosity change.

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