

The baryon content of the Universe

Massimo Persic^{1,2} and Paolo Salucci¹

¹SISSA, Strada Costiera 11, I-34014 Trieste, Italy

²Osservatorio Astronomico, via G.B. Tiepolo N.11, I-34131, Trieste, Italy

Accepted 1992 June 22. Received 1992 June 22; in original form 1992 May 20

SUMMARY

We estimate the baryon mass density of the Universe due to the stars in galaxies and the hot gas in clusters and groups of galaxies. The galaxy contribution is computed by using the Efstathiou, Ellis & Peterson luminosity function, together with van der Marel and Persic & Salucci's mass-to-light versus luminosity relationships. We find $\Omega_b^{\text{stars}} \approx 0.002$. For clusters and groups we use the Edge *et al.* X-ray luminosity function, and Edge & Stewart and Kriss, Cioffi & Canizares' (gas mass)-luminosity relations. We find $\Omega_b^{\text{gas}} \approx 0.001$. The total amount of visible baryons is then $\Omega_b \approx 0.003$, i.e. less than 10 per cent of the lower limit predicted by standard primordial nucleosynthesis, implying that the great majority of baryons in the Universe are unseen.

Key words: galaxies: fundamental parameters – intergalactic medium – cosmology: observations – dark matter.

1 INTRODUCTION

The estimation of the baryon mass density of the Universe essentially involves, for each class of objects having a visible baryon content, an integration over luminosity of the product of the luminosity function (LF), $\phi(L)$, the luminosity, L , and the mass-to-light ratio for the baryon component, M_b/L , according to the expression

$$\rho_b = \sum_T \int \phi(L) L \left(\frac{M_b}{L} \right) dL, \quad (1)$$

where T represents E/S0 galaxies, spiral galaxies, clusters and superclusters, and $\phi(L)$ and M_b/L refer to the relevant class of objects.

In the case of galaxies, equation (1) deserves some comments. First, let us note that the baryon mass-to-light ratio corresponds to the mass-to-light ratio of *stars*, and not to the *dynamical* one which usually includes dark matter (DM). In fact, the presence of DM in the internal parts of spiral galaxies is very evident (Persic & Salucci 1991), so we cannot ignore its contribution to the mass of a galaxy. In addition, the importance of DM is a function of luminosity: low-luminosity galaxies are affected more strongly than high-luminosity ones (Persic & Salucci 1988, 1990). Therefore it is essential that the mass-to-light ratio of the visible baryon content be the quantity that enters equation (1). Furthermore, we emphasize that different populations are present in galaxies of different Hubble types. These have different LFs, different mean M_b/L ratios, and different scaling properties

of (M_b/L) with luminosity. Finally, note that, since ρ_b scales as h_{50}^2 (see equation 1), when estimated by dynamical arguments the baryon density parameter $\Omega_b \equiv \rho_b/\rho_c$ (with $\rho_c = 5 h_{50}^2 \times 10^{-30} \text{ g cm}^{-3}$, the critical density) is independent of h_{50} .

In practice, the detailed information required by equation (1) has not previously been available. Standard estimates of ρ_b have assumed a typical value for the visible mass-to-light ratio of galaxies, usually inferred from the observed dynamics and supposed to be representative for galaxies of all luminosities and Hubble types. Then equation (1) reduces to

$$\rho_b = \mathcal{L} \left\langle \left(\frac{M_b}{L} \right) \right\rangle, \quad (2)$$

where \mathcal{L} is the galaxy luminosity density obtained by integrating the galaxy LF over luminosity and $\langle M_b/L \rangle$ is an assumed mass-to-light ratio. In addition, the hot gas in clusters and groups of galaxies has often been neglected in the computation of Ω_b .

For purposes of illustration, in Table 1 we summarize previous calculations of Ω_b according to equation (2). Note that in most cases the *dynamical* rather than the *stellar* mass-to-light ratio is used. The range in the adopted values found in the literature does not reflect observational uncertainties but, rather, real differences in stellar populations, in propor-

* Throughout the paper, $h_{50} \equiv H_0/(50 \text{ km s}^{-1} \text{ Mpc}^{-1})$, where H_0 is the Hubble constant.

Table 1. Summary of baryon density determinations.

Author	$\mathcal{L}^{(a)}$	$\langle M/L \rangle^{(b)}$	Type ^(c)	Ω_b
Peebles 1971	1.5 ^[1]	10 h_{50}	dynamical	0.02
Gott <i>et al.</i> 1974	0.5 ^[2]	(2.5–7.5) h_{50}	dynamical	≥ 0.001
Olive <i>et al.</i> 1981	2 ^[3]	(4–10) h_{50}	dynamical	0.003–0.007
Börner 1988	0.5 ^[4]	(7–10) h_{50}	dynamical	0.011–0.016
Hogan 1990	1.5 ^[5]	2	unspecified	0.008 h_{50}^{-1}
White 1990	1 ^[6]	5	stellar	0.003 h_{50}^{-1}
Kolb & Turner 1990	1.2 ^[7]	$\leq 5 h_{50}$	dynamical	≤ 0.01

Notes. ^(a)Adopted luminosity density, in $10^8 h_{50} L_{\odot} \text{Mpc}^{-3}$ (from ^[1]Peebles 1971; ^[2]Shapiro 1971; ^[3]Kirshner, Oemler & Schechter 1979; ^[4]Schechter 1976; ^[5]unspecified; ^[6]Efstathiou *et al.* 1988; ^[7]unspecified). ^(b)Adopted mass-to-light ratio, in solar units. ^(c)Type of adopted mass-to-light ratio, classified according to its procedure of determination.

tions of DM and in the reference radius where the dynamical mass-to-light ratio is considered.

Detailed information has recently been published on the properties of stellar mass-to-light versus luminosity relations for E/S0 and S galaxies (van der Marel 1991; Persic & Salucci 1991), as well as on the relation between hot-gas content and X-ray luminosity for clusters of galaxies (Edge & Stewart 1991a, b). Also, LFs have become available for E/S0 and S galaxies separately (Efstathiou, Ellis & Peterson 1988) as well as for clusters (Edge *et al.* 1990). It is therefore possible to obtain dynamical measures of the visible mass associated with these structures. The aim of this paper is to use these advances in estimating the value of Ω_b . The value we find, $\Omega_b \approx 0.003$, is lower than some previous estimates. Compared to current standard nucleosynthetic predictions, our estimate aggravates the problem of the ‘missing baryons’.

2 THE MEAN BARYON DENSITY FROM GALAXIES AND CLUSTERS

In all cases, the LF will have the usual Schechter (1976) form:

$$\phi(L) dL = \phi_* \left(\frac{L}{L_*} \right)^{-\alpha} e^{-L/L_*} \frac{dL}{L_*}, \quad (3)$$

where ϕ_* is a normalization constant, α is the slope of the LF at low luminosities, and L_* is the luminosity corresponding to the ‘knee’ of the LF; and the baryon mass-to-light versus luminosity relation will be a power law:

$$\frac{M_b}{L} = A \left(\frac{L}{L_*} \right)^{\eta}, \quad (4)$$

with A the mass-to-light ratio at the characteristic luminosity L_* . Inserting equations (3) and (4) into equation (2) we get

$$\rho_b = \phi_* L_* A \int_{x_{\min}}^{x_{\max}} x^{1-\alpha+\eta} e^{-x} dx, \quad (5)$$

where $x \equiv L/L_*$, and x_{\min} and x_{\max} represent the observed minimum and maximum luminosities for a given class of objects. The values of the parameters ϕ_* , α , L_* , x_{\min} , x_{\max} , A and η are observationally known and will be chosen accordingly for each class of objects.

We shall treat separately elliptical (and S0) galaxies, spiral galaxies, groups and clusters of galaxies.

2.1 Ellipticals

From Efstathiou *et al.*'s (1988) field-galaxy LF we get $\phi_* = 8.5 \times 10^{-4} h_{50}^3 \text{Mpc}^{-3}$, $\alpha = 0.48$ and $L_* = 3.3 \times 10^{10} h_{50}^{-2} L_{\odot}$; we take $x_{\min} = 0.04$ and $x_{\max} = 8$. There is strong evidence that ellipticals do not have DM inside their optical radii, so their dynamical masses at the optical radius and their stellar masses coincide (see Djorgovski & Davis 1987). From van der Marel (1991) we have $A = 4 h_{50} (M_{\odot}/L_{\odot})$ and $\eta = 0.35$ (all values refer to the B band). Inserting these values into equation (5), the integral takes a value of 0.97, and we then get $\rho_b \approx 7.4 \times 10^{-33} h_{50}^2 \text{g cm}^{-3}$. Thus the baryon contribution of elliptical galaxies to the mean density is

$$\Omega_b^{(E+S0)} \approx 1.5 \times 10^{-3} \quad (\text{E + S0 galaxies}). \quad (6)$$

2.2 Spirals

From Efstathiou *et al.* (1988) we get $\phi_* = 1.1 \times 10^{-3} h_{50}^3 \text{Mpc}^{-3}$, $\alpha = 1.24$ and $L_* = 4.2 \times 10^{10} h_{50}^{-2} L_{\odot}$; we take $x_{\min} = 0.01$ and $x_{\max} = 8$. Dark and visible matter are already well mixed in the optical regions of spirals (e.g. Persic & Salucci 1991). From Persic & Salucci's (1990) dynamical disc/halo mass decomposition of rotation curves, we get $A = 1.2 h_{50} (M_{\odot}/L_{\odot})$ and $\eta = 0.35$ (all values refer to the B band). Inserting these values into equation (5), the integral takes a value of 0.94, so we get $\rho_b \approx 3.5 h_{50}^2 \times 10^{-33} \text{g cm}^{-3}$, corresponding to

$$\Omega_b^{(S)} \approx 0.7 \times 10^{-3} \quad (\text{S galaxies}). \quad (7)$$

2.3 Rich clusters

The hot, X-ray emitting, diffuse intracluster gas is a distinctive prominent baryon component of clusters (e.g. Sarazin 1986). From Edge *et al.* (1990) we get $\phi_* = 6.9 \times 10^{-8} h_{50}^3 \text{Mpc}^{-3}$, $\alpha = 1.65$, $L_* = 8.1 \times 10^{44} h_{50}^{-2} \text{erg s}^{-1}$, $x_{\min} = 0.012$ and $x_{\max} = 2.5$; relative to the gas mass within $0.5 h_{50}^{-1} \text{Mpc}$ radius, from Edge & Stewart (1991a) we take $A = 50 h_{50}^{-0.3} \text{g erg}^{-1} \text{s}$ and $\eta = -0.62$. (All the X-ray data are relative to the 2–10 keV band.) Inserting the above values into equation (5),

the integral takes a value of 7.6, so we derive $\rho_b \approx 7.1 \times 10^{-34} h_{50}^{0.7} \text{ g cm}^{-3}$, corresponding to $\Omega_b \approx 1.4 \times 10^{-4} h_{50}^{-1.3}$. This estimate refers to the gas mass contained within $0.5 h_{50}^{-1} \text{ Mpc}$ radius (i.e., within ~ 2 optical core radii, see Bahcall 1977). In at least some cases, however, there is evidence (Jones & Forman 1984) for significant amounts of gas at larger distances, $\sim 3 h_{50}^{-1} \text{ Mpc}$. This distance is a good measure of the typical virialization radius of rich clusters [e.g., from a recent study of a large rich-cluster sample we have $R_{\text{vir}} = (3.0 \pm 0.2) h_{50}^{-1} \text{ Mpc}$ (Biviano *et al.* 1992)], and corresponds to the Abell (1958) radius, i.e. the radius roughly encompassing most of the cluster's member galaxies. The hot-gas surface-brightness profile can be described in terms of the so-called β -model,

$$S(r) = S_0 [1 + (r/a)^2]^{-3\beta+1/2},$$

with a (the core radius) and β as free parameters, which implies a deprojected spatial gas density distribution of the form

$$\rho_{\text{gas}}(r) = \rho_0 [1 + (r/a)^2]^{-3\beta/2}$$

(e.g., Henriksen & Mushotzky 1985; David *et al.* 1990). Fits to *Einstein* IPC data for a survey of clusters give for β an average value of $\langle \beta \rangle = 0.66 \pm 0.10$ (see Jones & Forman 1984; David *et al.* 1990). Therefore, on average, beyond a few core radii the hot-gas density falls off as $\rho_{\text{gas}} \propto r^{-2}$, and the mass in gas rises linearly with radius. We therefore estimate that the hot-gas contribution of rich clusters from within the Abell radius is

$$\Omega_b^{\text{(cl. gas)}} \approx 8.6 \times 10^{-4} h_{50}^{-1.3} \quad (\text{intracluster gas}). \quad (8)$$

In addition to the diffuse gas, further baryons in clusters are contributed by the stellar component of the member galaxies. However, recent direct estimates (see Edge & Stewart 1991b) indicate that, in the cores of clusters, the stellar mass is up to a factor of 3 smaller than the gas mass. Further out there are indications that the galaxy distribution drops more rapidly than the gas (e.g., Eyles *et al.* 1991), so that within a few core radii the stellar mass is significantly lower than the gas mass (roughly 10 per cent for a stellar mass-to-light ratio of 4; see David *et al.* 1990), and at the Abell radius the stellar component is negligible compared to the gas mass.

2.4 Poor clusters and groups

A population of poor clusters and groups of galaxies must certainly contribute to the baryon content. The information on the LF and the gas content at these mass scales is quite scanty. We extrapolate the Edge *et al.* (1990) cluster X-ray LF through the range of luminosities typical for these structures, $41 \leq \log L(2-10 \text{ keV}) \leq 43$ (see Kriss, Cioffi & Canizares 1983; Bahcall, Harris & Rood 1984; see Bahcall 1979 for a discussion of the continuity of cluster and group LFs). Thus in equation (5) we take the parameters of the Edge *et al.* (1990) cluster LF (see above), with $x_{\text{min}} = 1.2 \times 10^{-4}$ and $x_{\text{max}} = 0.012$. Relative to the hot-gas content within $0.5 h_{50}^{-1} \text{ Mpc}$ radius, the *Einstein* data of Kriss *et al.* (1983) imply $A = 65 h_{50}^{0.3}$ and $\eta = -0.5$ (in the 0.5–4.5 keV band). The integral in equation (5) takes a value of 13, so we derive $\rho_b \approx 1.6 \times 10^{-33} h_{50}^{0.7} \text{ g cm}^{-3}$, corresponding to $\Omega_b \approx 3.2 \times 10^{-4} h_{50}^{-1.3}$. Allowing for any hot gas extending

out to a typical group virialization radius ($\sim 1 h_{50}^{-1} \text{ Mpc}$, see Pisani 1990), by the same argument used for the rich clusters we get

$$\Omega_b^{\text{(gr. gas)}} \approx 6.4 \times 10^{-4} h_{50}^{-1.3} \quad (\text{intragroup gas}). \quad (9)$$

3 DISCUSSION

From equations (6)–(9), we conclude that the combined baryon contribution of galaxies and clusters to the mean density is

$$\Omega_b \approx 2.2 \times 10^{-3} + 1.5 \times 10^{-3} h_{50}^{-1.3}. \quad (10)$$

As $1 \leq h_{50} \leq 2$ with a currently favoured value of $h_{50} \approx 1.5$ (e.g., Pierce & Tully 1988), the cluster/group density contribution (*cf.* equations 8 and 9) is probably $\Omega_{\text{gas}} \approx 0.001$. The estimated contribution of the stellar populations of galaxies (see equations 6 and 7) is $\Omega_{\star} \approx 0.002$. This value is in very good agreement with the cosmological mass density of the damped Ly α systems, which are likely to be protogalaxy discs and would give a present-day contribution of $\Omega_b(\text{Ly}\alpha) \sim 0.002$ (see Wolfe 1988).

Note that the explicit inclusion of the general trend of decreasing stellar mass-to-light ratio with decreasing luminosity and the accounting for different morphological classes have the effect of reducing the estimated baryon contribution of galaxies. In fact, the often-assumed values of $(M_b/L_B) \sim 8 h_{50}$ for ellipticals and $(M_b/L_B) \sim 3 h_{50}$ for spirals actually refer only to the brightest objects (i.e. $L_B \geq 6 L_B^*$). Assuming such values as typical would overestimate the baryon contribution from stars by a factor of ~ 2 . As an example, let us take the mass-to-light ratios at L_B^* as the typical values (i.e., $4 h_{50}$ for ellipticals and $1.2 h_{50}$ for spirals) to be used in equation (2). Let us also use separate LFs to compute the luminosity densities due to ellipticals and spirals (i.e., $0.25 \times 10^8 h_{50} L_{B\odot}$ and $0.54 \times 10^8 h_{50} L_{B\odot} \text{ Mpc}^{-3}$ respectively, from Efstathiou *et al.* 1988). Then equation (2) would be written as

$$\begin{aligned} \rho_b &= \left[\mathcal{L} \left\langle \left(\frac{M_b}{L} \right) \right\rangle \right]_{E/S0} + \left[\mathcal{L} \left\langle \left(\frac{M_b}{L} \right) \right\rangle \right]_S \\ &= [0.25 \times 10^8 h_{50} L_{B\odot} \times 4] + [0.54 \times 10^8 h_{50} L_{B\odot} \times 1.2]. \end{aligned}$$

Thus we would find contributions to Ω_b of 1.4×10^{-3} and 0.9×10^{-3} for the two classes separately. This example shows that the discrepancy between some previous estimates of Ω_{\star} (claimed to agree with nucleosynthetic limits) and our own estimate arises mainly because those calculations used *dynamical* and unrealistic mass-to-light ratios and, to a lesser extent, because they did not use separate LFs for different morphologies.

Further baryons, in the form of hot ($T \geq 10^7 \text{ K}$) diffuse gas, could be supplied by superclusters. However, the observational limit to any diffuse X-ray emission from candidate supercluster cores (see Persic *et al.* 1990), alongside the spatial frequency of superclusters (i.e., $\sim 10^{-8} h_{50}^3 \text{ Mpc}^{-3}$), indicates a negligible contribution:

$$\Omega_b^{\text{(SC gas)}} \sim 10^{-5}.$$

Another reservoir of baryons could be cold diffuse H I gas in the local intergalactic medium (IGM). However, the absence of the Gunn–Peterson (1965) trough on local scales

places a severe upper bound to any such contribution: $\Omega_{\text{H I}} < 5 \times 10^{-7}$ (see Davidsen, Hartig & Fastie 1977).

We therefore expect that our derived value of Ω_{b} in equation (9) gives a close representation of the actual *visible* baryon content of the local Universe. [Fabian's (1991) recent estimate of the baryon density in the Shapley supercluster, $\Omega_{\text{b}} = 0.18 h_{50}^{-1.3}$, is not necessarily in contradiction with our estimate. In fact, Fabian's high value relates to a most exceptional region of $\sim 35 h_{50}^{-1}$ Mpc size and with $\delta\rho/\rho = 0.8 \Omega_0^{-1}$, while our low value refers to the whole nearby Universe out to a radius of $\sim 300 h_{50}^{-1}$ Mpc and with $\delta\rho/\rho \rightarrow 0$.] Our value, $\Omega_{\text{b}} = 0.003$, is substantially lower than the prediction of standard cosmic nucleosynthesis, $0.04 \leq \Omega_{\text{b}} h_{50}^2$ with a probable value of $\Omega_{\text{b}} h_{50}^2 \approx 0.06$ (e.g., Kolb & Turner 1990; Peebles *et al.* 1991). Comparing the observed and the predicted baryon abundances, we conclude that *the stars and gas of galaxies and clusters/groups account for only $\lesssim 10$ per cent of the primordially synthesized baryons* (see also Hogan 1990; Kolb & Turner 1990).

Where are the ≥ 90 per cent of missing baryons? We have only taken an inventory of the *visible* baryons associated with *visible* structures. Additional baryons, unaccounted for by the present census, can either be clumped in some dark form, for instance forming dark haloes around galaxies, or be distributed in a diffuse ionized background. [Note that the diffuse DM associated with clusters, exceeding the gas mass by at most a factor of ~ 3 (e.g., Eyles *et al.* 1991), could not solve the discrepancy with standard nucleosynthesis even if it were completely baryonic.] Let us consider each of the two possibilities in turn.

(i) *Baryons in haloes.* The dark haloes of spiral galaxies may well extend out to 10–20 times the size of the optical discs. Thus it is not difficult to conceive that, by integrating the dynamical mass-to-light ratio of galaxies (computed at such extended radii) over the LF, the nucleosynthetic value of $\Omega_{\text{b}} h_{50}^2 \approx 0.06$ might be easily reached. An attractive way of hiding the missing baryons, therefore, is to assume that they constitute the DM in galaxy haloes. This possibility may find support from the evidence that cooling flows may be producing baryonic DM in the form of low-mass stars or brown dwarfs (e.g., Fabian, Nulsen & Canizares 1984). Based on cooling flow analogies, Thomas & Fabian (1990) have argued that baryonic DM only forms on fairly large mass-scales where gas cooling is quasi-static, while Ashman (1990) has suggested that baryonic DM forms on galactic and subgalactic scales, following rapid gas cooling (Ashman & Carr 1991).

(ii) *Ionized IGM.* The second possibility is to suppose that galaxy formation is extremely inefficient, so that only 10 per cent of gas in the Universe is now in collapsed structures such as galaxies. This could arise if gas was *never* incorporated into galaxies, or if gas was expelled from protogalaxies by supernova explosions or galactic winds (Bookbinder *et al.* 1980). In this scenario, most baryons in the Universe now constitute a smooth ionized IGM, in agreement with the lack of any Gunn–Peterson trough in the spectra of quasars both at high redshifts (see Sargent & Steidel 1990) and locally (Davidsen *et al.* 1977). There is no shortage of proposed sources of ionization. Among conventional ad hoc sources there are Population III stars (Carr 1990), dwarf and starburst galaxies (Silk, Wyse & Shields 1987; Songaila, Cowie & Lilly 1990) and obscured quasars (Miralda-Escudé &

Ostriker 1990). Alternatively, a non-conventional self-consistent explanation involves the radiative decay of cosmological dark matter particles (Rephaeli & Szalay 1981; Sciamia 1982).

We conclude by stressing that the result presented in this paper, in connection with the dynamical estimates of the *total* mass density of the Universe on scales $\sim 10 h_{50}^{-1}$ Mpc, $\Omega_0 \geq 0.2$ (see Davis *et al.* 1980; Davis & Peebles 1983) supports the conventional view on the need for *non-baryonic* extra dark matter.

ACKNOWLEDGMENTS

We thank Dennis Sciamia for stimulating conversions that motivated us to undertake this calculation and for continuous encouragement. We also thank Keith Ashman for discussing with us the role of baryonic dark matter. Finally, we acknowledge the referee's useful advice which has helped us to improve the presentation of this work.

REFERENCES

- Abell, G. O., 1958. *Astrophys. J. Suppl.*, **3**, 211.
 Ashman, K. M., 1990. *Astrophys. J.*, **359**, 15.
 Ashman, K. M. & Carr, B. J., 1991. *Mon. Not. R. astr. Soc.*, **249**, 13.
 Bahcall, N. E., 1977. *Ann. Rev. Astr. Astrophys.*, **15**, 505.
 Bahcall, N. E., 1979. *Astrophys. J.*, **232**, 689.
 Bahcall, N. E., Harris, D. E. & Rood, H. J., 1984. *Astrophys. J. Lett.*, **284**, L29.
 Biviano, A., Girardi, M., Giuricin, G., Mardirossian, F. & Mezzetti, M., 1992. *Astrophys. J.*, in press.
 Bookbinder, J., Cowie, L. L., Krolik, J. H., Ostriker, J. P. & Rees, M., 1980. *Astrophys. J.*, **237**, 647.
 Börner, G., 1988. *The Early Universe*, Springer-Verlag, Berlin.
 Carr, B. J., 1990. *Comm. Astrophys.*, **14**, 257.
 David, L. P., Arnaud, K. A., Forman, W. & Jones, C., 1990. *Astrophys. J.*, **356**, 32.
 Davidsen, A. F., Hartig, G. F. & Fastie, W. G., 1977. *Nature*, **269**, 203.
 Davis, M. & Peebles, P. J. E., 1983. *Astrophys. J.*, **267**, 465.
 Davis, M., Tonry, J., Huchra, J. & Latham, D. W., 1980. *Astrophys. J. Lett.*, **238**, L113.
 Djorgovski, S. & Davis, M., 1987. *Astrophys. J.*, **313**, 59.
 Edge, A. C. & Stewart, G. C., 1991a. *Mon. Not. R. astr. Soc.*, **252**, 414.
 Edge, A. C. & Stewart, G. C., 1991b. *Mon. Not. R. astr. Soc.*, **252**, 428.
 Edge, A. C., Stewart, G. C., Fabian, A. C. & Arnaud, K. A., 1990. *Mon. Not. R. astr. Soc.*, **245**, 559.
 Efstathiou, G., Ellis, R. S. & Peterson, B. A., 1988. *Mon. Not. R. astr. Soc.*, **232**, 431.
 Eyles, C. J. *et al.*, 1991. *Astrophys. J.*, **376**, 23.
 Fabian, A. C., 1991. *Mon. Not. R. astr. Soc.*, **253**, 29P.
 Fabian, A. C., Nulsen, P. E. J. & Canizares, C. R., 1984. *Nature*, **311**, 733.
 Gott, J. R., Gunn, J. E., Schramm, D. N. & Tinsley, B. M., 1974. *Astrophys. J.*, **194**, 543.
 Gunn, J. E. & Peterson, B. A., 1965. *Astrophys. J.*, **142**, 1633.
 Henriksen, M. J. & Mushotzky, R. F., 1985. *Astrophys. J.*, **292**, 441.
 Hogan, C. J., 1990. In: *Baryonic Dark Matter*, p. 1, eds Lynden-Bell, D. & Gilmore, G., Kluwer, Dordrecht.
 Jones, C. & Forman, W., 1984. *Astrophys. J.*, **276**, 38.
 Kirshner, R. P., Oemler, A., Jr & Schechter, P. L., 1979. *Astr. J.*, **84**, 951.

- Kolb, E. W. & Turner, M. S., 1990. In: *The Early Universe*, Addison-Wesley Publishing Company, California.
- Kriss, G. A., Cioffi, D. F. & Canizares, C. R., 1983. *Astrophys. J.*, **272**, 439.
- Miralda-Escudé, J. & Ostriker, J. P., 1990. *Astrophys. J.*, **350**, 1.
- Olive, K. A., Schramm, D. N., Steigman, G., Turner, M. S. & Yang, J., 1981. *Astrophys. J.*, **246**, 557.
- Peebles, P. J. E., 1971. *Observational Cosmology*, Princeton University Press, Princeton, NJ.
- Peebles, P. J. E., Schramm, D. N., Turner, E. L. & Kron, R. G., 1991. *Nature*, **352**, 769.
- Persic, M. & Salucci, P., 1988. *Mon. Not. R. astr. Soc.*, **234**, 131.
- Persic, M. & Salucci, P., 1990. *Mon. Not. R. astr. Soc.*, **245**, 577.
- Persic, M. & Salucci, P., 1991. *Astrophys. J.*, **368**, 60.
- Persic, M., Jahoda, K., Rephaeli, Y., Boldt, E., Marshall, F. E., Mushotzky, R. F. & Rawley, G., 1990. *Astrophys. J.*, **364**, 1.
- Pierce, M. J. & Tully, R. B., 1988. *Astrophys. J.*, **330**, 579.
- Pisani, A., 1990. *PhD thesis*, SISSA, Trieste.
- Rephaeli, Y. & Szalay, A. S., 1981. *Phys. Lett.*, **106B**, 73.
- Sarazin, C. L., 1986. *Rev. Mod. Phys.*, **58**, 1.
- Sargent, W. L. W. & Steidel, C. C., 1990. In: *Baryonic Dark Matter*, p. 223, eds Lynden-Bell, D. & Gilmore, G., Kluwer, Dordrecht.
- Schechter, P. L., 1976. *Astrophys. J.*, **203**, 297.
- Sciama, D. W., 1982. *Mon. Not. R. astr. Soc.*, **198**, 1p.
- Shapiro, S., 1971. *Astr. J.*, **76**, 291.
- Silk, J., Wyse, R. & Shields, G. H., 1987. *Astrophys. J. Lett.*, **322**, L59.
- Songaila, A., Cowie, L. L. & Lilly, S. J., 1990. *Astrophys. J.*, **348**, 371.
- Thomas, P. A. & Fabian, A. C., 1990. *Mon. Not. R. astr. Soc.*, **246**, 156.
- van der Marel, R. P., 1991. *Mon. Not. R. astr. Soc.*, **253**, 710.
- White, S. D. M., 1990. In: *Physics of the Early Universe, Proc. 36th Scottish Universities Summer School in Physics*, eds Peacock, J. A., Heavens, A. F. & Davies, A. T.
- Wolfe, A. M., 1988. In: *QSO Absorption Lines: Probing the Universe, Proc. Space Telescope Science Institute Symp. No. 2*, p. 297, eds Blades, J. C., Turnshek, D. & Norman, C. A., Cambridge University Press, Cambridge.