New Cosmological Data and the Values of the Fundamental Parameters
IAU Symposium, Vol. 201, 2005
Anthony Lasenby and Althea Wilkinson, eds.

The Mass Density of the Universe

Neta A. Bahcall
Princeton University Observatory, Astrophysical Sciences Department, Peyton Hall, Princeton, NJ 08544-1001, USA

Abstract. One of the most fundamental questions in cosmology is: How much matter is there in the Universe and how is it distributed? Here I show that several independent measures—including those utilizing clusters of galaxies—all indicate that the mass-density of the Universe is low—only ~20% of the critical density. Recent measurements of the mass-to-light function—from galaxies, to groups, clusters, and superclusters—provide a powerful new measure of the universal density. The results reveal a low density of 0.16±0.05 the critical density. The observations suggest that, on average, the mass distribution follows the light distribution on large scales. The results, combined with the recent observations of high redshift supernovae and the spectrum of the CMB anisotropy, suggest a Universe that has low density ($\Omega_m \simeq 0.2$), is flat, and is dominated by dark energy.

1. Introduction

Theoretical arguments based on standard models of inflation, as well as on the demand of no "fine tuning" of cosmological parameters, predict a flat universe with the critical density needed to just halt its expansion. The critical density, $1.9 \times 10^{-29} h^2 g\ cm^{-3}$ (where h refers to Hubble's constant, see below), provides the gravitational pull needed to slow down the universal expansion and will eventually bring it to a halt. So far, however, only a small fraction of the critical density has been detected, even when all the unseen dark matter in galaxy halos and clusters of galaxies is included. There is no reliable indication that most of the matter needed to close the universe does in fact exist. Here we show that several independent observations of clusters of galaxies all indicate that the mass density of the universe is sub-critical. These observations include the mass and mass-to-light ratio of galaxies, clusters, and superclusters of galaxies, the high baryon fraction observed in clusters, and the evolution of the number density of massive clusters with time; the latter method provides a powerful measure not only of the mass-density of the universe but also the amplitude of the mass fluctuations. The three independent methods– all simple and robust– yield consistent results of a low-density universe with mass approximately tracing light on large scales. The results are consistent with those derived from the high redshift supernovae observation, the CMB anisotropy spectrum, and recent weak lensing observations on large scales.

2. Cluster Dynamics and the Mass-to-Light Function

Rich clusters of galaxies are the most massive virialized objects known. Cluster masses can be directly and reliably determined using three independent methods: the motion of galaxies within clusters (Zwicky 1957; Bahcall 1977; Carlberg et al. 1996); the temperature of the hot intracluster gas (Jones et al. 1984; Sarazin 1986; Evrard 1996); and gravitational lensing distortions of background galaxies (Tyson et al. 1990; Kaiser et al. 1993; Smail et al. 1995; Colley et al. 1996). All three independent methods yield consistent cluster masses (typically within radii of ~1 Mpc), indicating that we can reliably determine cluster masses within the observed scatter ($\sim \pm$ 30%).

The simplest argument for a low density universe is based on summing up all the observed mass(associated with light to the largest possible scales) by utilizing the well-determined masses of clusters. The masses of rich clusters of galaxies range from $\sim 10^{14}$ to 10^{15} $h^{-1}M_\odot$ within $1.5h^{-1}$Mpc radius of the cluster center (where $h = H_0/100$ km s^{-1} Mpc^{-1} denotes Hubble's constant). When normalized by the cluster luminosity, a median mass-to-light ratio of $M/L_B \simeq 300 \pm 100h$ in solar units ($M_\odot/L_\odot$) is observed for rich clusters (Bahcall et al. 1995; Carlberg et al. 1996). (L_B is the total luminosity of the cluster in the blue band, corrected for internal and Galactic absorption.) When integrated over the entire observed luminosity density of the universe, this mass-to-light ratio yields a mass density of $\rho_m \simeq 0.4 \times 10^{-29} h^2$g cm^{-3}, or a mass density ratio of $\Omega_m = \rho_m/\rho_{crit} \simeq 0.2 \pm 0.07$ (where ρ_{crit} is the critical density needed to close the universe). The inferred density assumes that all galaxies exhibit the same high M/L_B ratio as clusters, and that mass follows light on large scales. Thus, even if all galaxies have as much mass per unit luminosity as do massive clusters, the total mass of the universe is only ~20% of the critical density. If one insists on esthetic grounds that the universe has a critical density ($\Omega_m = 1$), then most of the mass of the universe has to be unassociated with galaxies (i.e., with light). On large scales ($\gtrsim 1.5$ h^{-1} Mpc) the mass has to reside in "voids" where there is no light. This would imply, for $\Omega_m = 1$, a large bias in the distribution of mass versus light, with mass distributed considerably more diffusely than light.

Is there a strong bias in the universe, with most of the dark matter residing on large scales, well beyond galaxies and clusters? A recent analysis of the mass-to-light ratio of galaxies, groups, and clusters by Bahcall et al. 1995 suggests that there is not a large bias. The study shows that the M/L_B ratio of galaxies increases with scale up to radii of $R \sim 0.2$ h^{-1} Mpc, due to very large dark halos around galaxies (Ostriker et al. 1974; Rubin 1993). The M/L ratio, however, appears to flatten and remain approximately constant for groups and rich clusters from scales of ~0.2 to at least 1.5 h^{-1} Mpc and even beyond (Figure 1). The flattening occurs at $M/L_B \simeq 200 - 300h$, corresponding to $\Omega_m \simeq 0.2$. (An $M/L_B \sim 1350h$ is needed for a critical density universe, $\Omega_m = 1$.) This observation contradicts the classical belief that the relative amount of dark matter increases continuously with scale, possibly reaching $\Omega_m = 1$ on large scales. The available data suggest that most of the dark matter may be associated with very large dark halos of galaxies and that clusters do not contain a substantial amount of additional dark matter, other than that associated with (or torn-off from) the galaxy halos, plus the hot intracluster gas. This flattening of M/L with scale suggests that the relative amount of dark matter does not increase significantly

https://doi.org/10.1017/S0074180900216410 Published online by Cambridge University Press

with scale above ~ 0.2 h^{-1} Mpc. In that case, the mass density of the universe is low, $\Omega_m \sim 0.2-0.3$, with no significant bias (i.e., mass approximately following light on large scales).

The mass and mass-to-light ratio of a supercluster of galaxies, on a scale of $\sim$6h^{-1}Mpc, was recently measured using observations of weak gravitational lensing distortion of background galaxies (Kaiser et al. 1998). The results yield a supercluster mass-to-light ratio (on 6h^{-1}Mpc scale) of $M/L_B = 280 \pm 40$h, comparable to the mean value obtained for the three individual clusters that are members of this supercluster. These results provide a powerful confirmation of the suggested flattening of M/L_B (R) seen in Figure 1 (Bahcall et al. 1995, 1998).

Recently, Bahcall et al. 2000 used large-scale cosmological simulations to estimate the mass-to-light ratio of galaxy systems as a function of scale, and compare the results with observations of galaxies, groups, clusters, and superclusters of galaxies. They find remarkably good agreement between observations and simulations (Figure 1). Specifically, they find that the simulated mass-to-light ratio increases with scale on small scales and flattens to a constant value on large scales, as suggested by observations. The results show that while mass typically follows light on large scales, high overdensity regions—such as rich clusters and superclusters of galaxies—exhibit higher M/L_B values than average, while low density regions exhibit lower M/L_B values; high density regions are thus antibiased in M/L_B, with mass more strongly concentrated than blue light. The M/L_B antibias is mainly due to the relatively old age of the high density regions, where light has declined significantly since their early formation time, especially in the blue band which traces recent star formation. Comparing the simulated results with observations, Bahcall et al. 2000 place a powerful constraint on the mass density of the universe; using, for the first time, the entire observed mass-to-light function, from galaxies to superclusters, they find

$$\Omega_m = 0.16 \pm 0.05. \tag{1}$$

3. Baryons in Clusters

Clusters contain many baryons, observed as gas and stars. Within 1.5h^{-1} Mpc of a rich cluster, the X-ray emitting gas contributes $\sim$ 7h$^{-1.5}$ % of the cluster virial mass (White et al. 1993, 1995; Lubin et al. 1996). Stars in the predominatly early type cluster galaxies contribute another $\sim$3%. The baryon fraction observed in clusters is thus:

$$\Omega_b/\Omega_m \gtrsim 0.07\mathrm{h}^{-1.5} + 0.03 \tag{2}$$

Standard Big Bang nucleosynthesis limits the baryon density of the universe to (Walker et al. 1991; Tytler et al. 1996):

$$\Omega_b \simeq 0.02\mathrm{h}^{-2} \tag{3}$$

These facts suggest that the baryon fraction observed in rich clusters (Eq. 2) exceeds that of an $\Omega_m = 1$ universe ($\Omega_b/(\Omega_m = 1) \simeq 0.02\mathrm{h}^{-2}$; Eq. 3) by a factor of $\gtrsim 3$ (for h $\simeq 0.5$). Since detailed hydrodynamic simulations (White

https://doi.org/10.1017/S0074180900216410 Published online by Cambridge University Press

et al. 1993; Lubin et al. 1996) show that baryons do not segregate into rich clusters, the above results imply that either the mean density of the universe is lower than the critical density by a factor of $\gtrsim 3$, or that the baryon density is much larger than predicted by nucleosynthesis. The observed high baryonic mass fraction in clusters, combined with the nucleosynthesis limit, indicate (for h $\simeq 0.65 \pm 0.1$):

$$\Omega_m \lesssim 0.3 \pm 0.05. \tag{4}$$

This upper limit on Ω_m is a simple model-independent and thus powerful constraint: a critical density universe is inconsistent with the high baryon fraction observed in clusters. Observations of the Sunyaev-Zeldovich effect in clusters yield the same result (Carlstrom et al., this volume).

4. Evolution of Cluster Abundance

The observed present-day abundance of rich clusters of galaxies places a strong constraint on cosmology: $\sigma_8 {\Omega_m}^{0.5} \simeq 0.5$, where σ_8 is the *rms* mass fluctuations on 8 h^{-1} Mpc scale, and Ω_m is the present cosmological density parameter (Bahcall & Cen 1992; White et al. 1993; Eke et al. 1996; Viana et al. 1996; Kitayama et al. 1996; Pen 1998). This constraint is degenerate in Ω_m and σ_8; models with Ω_m =1, $\sigma_8 \sim 0.5$ are indistinguishable from models with $\Omega_m \sim 0.25$, $\sigma_8 \sim 1$. (A $\sigma_8 \simeq 1$ universe is unbiased, with mass following light on large scales since galaxies (light) exhibits σ_8 (galaxies) $\simeq 1$; $\sigma_8 \simeq 0.5$ implies a mass distribution wider than light).

The *evolution* of cluster abundance with redshift, especially for massive clusters, breaks the degeneracy between Ω_m and σ_8 (Peebles et al. 1989; Eke et al. 1996; Viana et al. 1996; Oukbir et al. 1992, 1997; Carlberg et al. 1997; Bahcall et al. 1997; Fan et al. 1997; Henry 1997; Bahcall et al. 1998). The evolution of high mass clusters is strong in Ω_m =1, low-σ_8 (biased) Gaussian models, where only a very low cluster abundance is expected at z >0.5. Conversely, the evolution rate in low-Ω_m, high-σ_8 models is mild and the cluster abundance at z >0.5 is much higher than in Ω_m=1 models.

In low-density models, density fluctuations evolve and freeze out at early times, thus producing only relatively little evolution at recent times ($z \lesssim 1$). In an Ω_m=1 universe, the fluctuations start growing more recently thereby producing strong evolution in recent times; a large increase in the abundance of massive clusters is expected from $z \sim 1$ to $z \sim 0$. Bahcall et al. 1997 show that the evolution is so strong in Ω_m=1 models that finding even a few Coma-like clusters at $z > 0.5$ over $\sim 10^3$ deg^2 of sky contradicts an Ω_m=1 model where only $\sim 10^{-2}$ such clusters would be expected (when normalized to the present-day cluster abundance).

The evolutionary effects increase with cluster mass and with redshift. The existence of the three most massive clusters observed so far at $z \sim 0.5-0.9$ places the strongest constraint yet on Ω_m and σ_8. These clusters (MS0016+16 at $z = 0.55$, MS0451−03 at $z = 0.54$, and MS1054–03 at $z = 0.83$, from the Extended Medium Sensitivity Survey, EMSS (Henry et al. 1992; Luppino et al. 1995), are nearly twice as massive as the Coma cluster, and have reliably measured masses (including gravitational lensing masses, temperatures, and velocity dispersions; (Bahcall et al. 1998; Smail et al. 1995; Luppino et al. 1997; Mushotsky et

https://doi.org/10.1017/S0074180900216410 Published online by Cambridge University Press

al. 1997; Donahue et al. 1999). These clusters posses the highest masses ($\gtrsim 8 \times 10^{14}$ h^{-1} M$_\odot$ within 1.5 h^{-1} commoving Mpc radius), the highest velocity dispersions ($\gtrsim$ 1200 km s^{-1}), and the highest temperatures ($\gtrsim$ 8 keV) in the $z > 0.5$ EMSS survey. The existence of these three massive distant clusters, even just the existence of the single observed cluster at $z = 0.83$, rules out Gaussian Ω_m=1 models for which only $\sim 10^{-5}$ $z \sim 0.8$ clusters are expected instead of the 1 cluster observed (or $\sim 10^{-3}$ $z > 0.5$ clusters expected instead of the 3 observed) (Bahcall et al. 1998). Figure 2 compares the observed versus expected evolution of such massive clusters.

The data provide powerful constraints on Ω_m and σ_8: Ω_m=$0.2^{+0.15}_{-0.1}$ and $\sigma_8 = 1.2 \pm 0.3$ (68% confidence level) (Bahcall et al. 1998). The high σ_8 value for the mean mass fluctuations indicates a nearly unbiased universe, with mass approximately tracing light on large scales. This conclusion is consistent with the suggested flattening of the observed M/L ratio on large scales (Figure 1).

5. Summary

We have shown that several independent observations of clusters of galaxies all indicate that the mass-density of the universe is sub-critical: $\Omega_m \simeq 0.2 \pm 0.1$. A summary of the results is highlighted below.

1. The mass-to-light function of galaxies, groups, clusters and superclusters of galaxies yields a tight constraint; $\Omega_m = 0.16 \pm 0.05$.

2. The high baryon fraction observed in clusters of galaxies suggests $\Omega_m \lesssim 0.3 \pm 0.05$.

3. The weak evolution of the observed cluster abundance to $z \sim 1$ provides an independent estimate: $\Omega_m \simeq 0.2^{+0.15}_{-0.1}$, valid for any Gaussian models. An Ω_m=1 Gaussian universe is ruled out as a $\lesssim 10^{-6}$ probability by the cluster evolution results.

4. All the above-described independent measures are consistent with each other and indicate a low-density universe with $\Omega_m \simeq 0.2 \pm 0.1$.

5. The above results are consistent with those derived from high redshift supernovae observations (assuming a flat universe) and from the recent CMB observations (indicating a flat universe, (Lange et al. 2000). Combining the above results of clusters, SNe, and CMB in the Cosmic Triangle (Bahcall et al. 1999), we find a universe that is lightweight (Ω_m=0.2) and flat.

References

Bahcall, N. A. 1977, ARA&A, 15, 505

Bahcall, N. A. & Cen, R. 1992, ApJ, 398, L81

Bahcall, N. A., Cen, R., Davé, R., Ostriker, J. P., & Yu, Q. 2000, ApJ, 541, 1

Bahcall, N. A. & Fan, X. 1998, Proc. Nat. Acad. Sci. USA, 95, 5956

Bahcall, N. A. & Fan, X. 1998, ApJ, 504, 1

https://doi.org/10.1017/S0074180900216410 Published online by Cambridge University Press

Bahcall, N. A., Fan, X., & Cen, R. 1997, ApJ, 485, L53
Bahcall, N. A., Lubin, L., & Dorman, V. 1995, ApJ, 447, L81
Bahcall, N. A., Ostriker, J. P., Perlmutter, S., Steinhardt, P. 1999, Science, 241, 1481
Carlberg, R. G. et al. 1996, ApJ, 462, 32
Carlberg, R. G., Morris, S. M., Yee, H. K. C., & Ellingson, E. 1997, ApJ, 479, L19
Colley, W. N., Tyson, J. A., & Turner, E. L 1996, ApJ, 461, L83
Donahue, M. & Voit, G. M. 1999, ApJ. 523, L137
Eke, V. R., Cole, S., & Frenk, C. S. 1996, MNRAS, 282, 263
Evrard, A. E., Metzler, C. A., & Navarro, J. F. 1996, ApJ, 469, 494
Fan, X., Bahcall, N. A., & Cen, R. 1997, ApJ, 490, L123
Henry, J. P, et al. 1992, ApJ, 386, 408
Henry, J. P. 1997, ApJ, 489, L1
Jones, C. & Forman, W. 1984, ApJ, 276, 38
Kaiser, N. & Squires, G. 1993, ApJ, 404, 441
Kaiser, N., et al. 1998, astro-ph/9809268
Kitayama, T. & Suto, Y. 1996, ApJ, 469, 480
Lange, A. et al. 2000, astro-ph/0005004
Lubin, L., Cen, R., Bahcall, N. A., & Ostriker, J. P. 1996, ApJ, 460, 10
Luppino, G. A. & Gioia, I. M. 1995, ApJ, 445, L77
Luppino, G. A. & Kaiser, N. 1997, ApJ, 475, 20
Mushotsky, R. & Scharf, C. A. 1997, ApJ, 482, L13
Ostriker, J. P., Peebles, P. J. E., & Yahil, A. 1974, ApJ, 193, L1
Oukbir, J. & Blanchard, A. 1992, A&A, 262, L21
Oukbir, J. & Blanchard, A. 1997, A&A, 317, 1
Peebles, P. J. E., Daly, R. A., & Juszkiewicz, R. 1989, ApJ, 347, 563
Pen, U. -L. 1998, ApJ, 498, 60
Rubin, V. C. 1993, Proc. Natl. Acad. Sci. USA, 90, 4814
Sarazin, C. L. 1996, Rev. Mod. Phys., 58, 1
Smail, I., Ellis, R. S., Fitchett, M. J., & Edge, A. C. 1995, MNRAS, 273, 277
Tyson, J. A., Wenk, R. A., & Valdes, F. 1990, ApJ, 349, L1
Tytler, D., Fan, X. -M., & Burles, S. 1996, Nature, 381, 207
Viana, P. P. & Liddle, A. R. 1996, MNRAS, 281, 323
Walker, T. P., et al. 1991, ApJ, 376, 51
White, D. & Fabian, A. 1995, MNRAS, 272, 72
White, S. D. M., Efstathiou, G., & Frenk, C. S. 1993, MNRAS, 262, 1023
White, S. D. M., Navarro, J. F., Evrard, A., & Frenk, C. S. 1993, Nature, 366, 429
Zwicky, F. 1957, "Morphological Astronomy" (Berlin: Springer-Verlag)

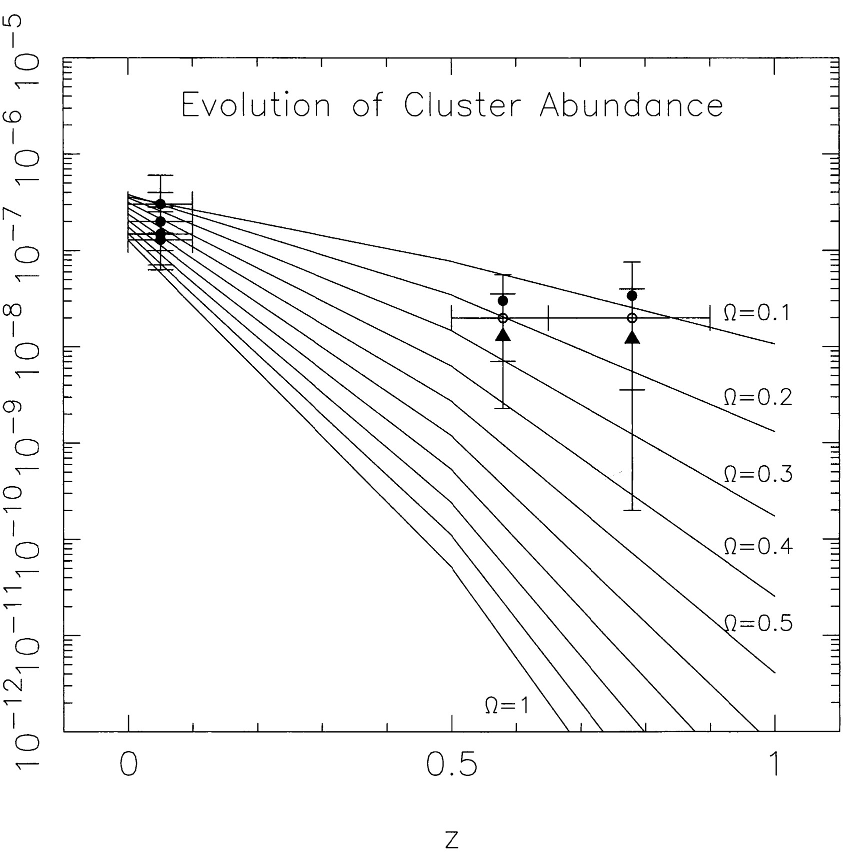

Figure 1. Evolution of the cluster abundance with redshift for massive clusters (with mass $>8\times10^{14}h^{-1}\,M_\odot$ within a comoving radius of $1.5h^{-1}$ Mpc). (From Bahcall & Fan 1998.) The data points represent the observational data (see text), and the curves represent the expected cluster abundance for different Ω_m values (based on the Press-Schechter method). Similar results are obtained from direct simulations (Bode et al., in preparation).

https://doi.org/10.1017/S0074180900216410 Published online by Cambridge University Press

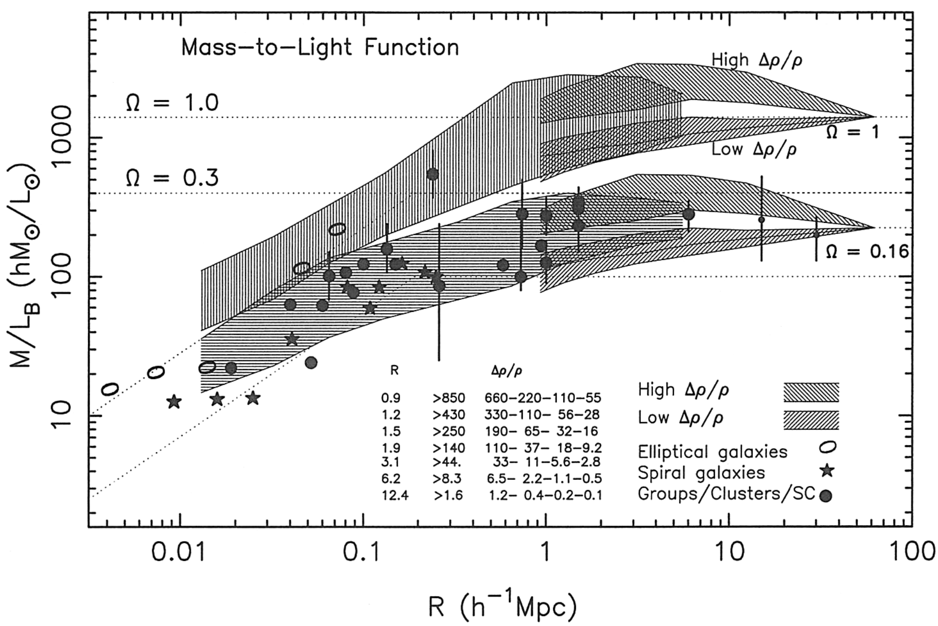

Figure 2. The mass-to-light function of galaxy systems from observations (Bahcall et al. 1995) and simulations (Bahcall et al. 2000). The observations are presented by the data points for medians of galaxies, groups, clusters, and a supercluster. The simulation results (for cold-dark-matter models) are presented by the shaded bands for $\Omega_m = 1$ and 0.16 (our best fit value). On scales >1Mpc, the simulation results for both high- and low- density regions are presented (where these correspond roughly to the overdensities of rich-clusters and groups, respectively). See Bahcall et al. (2000) for more details.