The baryon content of galaxy clusters: a challenge to cosmological orthodoxy

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Baryonic matter constitutes a larger fraction of the total mass of rich galaxy clusters than is predicted by a combination of cosmic nucleosynthesis considerations (light-element formation during the Big Bang) and standard inflationary cosmology. This cannot be accounted for by gravitational and dissipative effects during cluster formation. Either the density of the Universe is less than that required for closure, or there is an error in the standard interpretation of element abundances.

A dramatic success of the hot Big Bang theory is its ability to explain the relative abundances of the light elements. Current estimates of the 'primordial' abundances of ^{1}H, ^{2}H, ^{3}He, ^{4}He and ^{7}Li are all consistent with those expected a few minutes after the Big Bang, provided that the present universe has baryon density in the range $0.01 < \Omega_b h^2 < 0.015$ (ref. 1). Here, the present value of Hubble's constant, H_0, is taken to be $100\,h$ km s^{-1} Mpc^{-1}, Ω_b is given in units of the critical density needed to close the Universe, and the range is a 95% confidence interval. Baryon densities much larger than this overproduce both ^{7}Li and ^{4}He, whereas significantly smaller values overproduce the combined abundance of ^{2}H and ^{3}He. Thus, in the context of the standard theory, Ω_b is strongly constrained by the observed abundances of the light elements.

Over the last decade the cosmology community has increasingly accepted the plausibility of the inflation model and of its associated prediction that the Universe should have negligible curvature. In the absence of a cosmological constant this requires the mean matter density, Ω_0, to be very close to the critical value for closure. The discrepancy between $\Omega_0 = 1$ and $\Omega_b h^2 \sim 0.0125$ is, of course, the main motivation for the hypothesis that most of the mass in the universe is in some non-baryonic and invisible form, for example massive neutrinos or axions[2]. For a long time direct dynamical evidence for such large amounts of dark matter was lacking. Recently, however, comparisons of large-scale motions of galaxies with the density field which induces them have consistently led to large estimates for Ω_0, often consistent with unity[3-6].

Rich clusters of galaxies are the largest objects for which total masses can be estimated directly. The need for unseen dark matter was first identified in such systems[7], and recent analyses have concluded that stars in the individual galaxies contribute 5–10% of the mass needed to generate the observed orbital motions[2,8-10]. Baryonic matter is also seen in the form of a hot intracluster medium which emits thermal bremsstrahlung and line radiation at X-ray energies. The density and temperature of this gas can be estimated directly from the surface brightness and spectrum of its X-ray emission, and it has been known for 20 years that its total mass is comparable to that of the galaxies. Recent reviews[10-12] quote mass fractions for the X-ray-emitting gas in the range 0.04–$0.1\,h^{-3/2}$. As some fraction of the dark matter in rich clusters may well also be baryonic, these numbers suggest an approximate lower limit to the baryon fraction in clusters of $\sim 0.05 + 0.04\,h^{-3/2}$.

Here we explore the apparent contradiction between the low baryon fraction implied by currently popular cosmological theories and the larger baryon fractions measured in rich galaxy clusters, a discrepancy which has previously been discussed by a number of authors[13-18]. The wide field of view and high sensitivity of the Rosat satellite is now producing much improved determinations of the gas distribution in clusters. These are reinforcing previous estimates of the amount of hot gas and, most importantly, are allowing the enclosed gas mass to be measured reliably to much larger radii than before. We use the Coma cluster as an example and derive estimates of the galaxy mass, gas mass, and total masses within a fiducial radius $r_A = 1.5\,h^{-1}$ Mpc, the standard Abell radius. We emphasize that there is no reason to believe that the baryon fraction in this system is in any way anomalous. Indeed, far from the centre, all the rich clusters for which we have so far seen Rosat data bear a close resemblance to Coma (for example, ref. 19).

We then investigate whether the baryon fraction in a cluster can greatly exceed the universal value and conclude that gravitational and dissipative effects during cluster formation cannot account for the apparent discrepancy. We are forced to one of a series of unpalatable conclusions. The mean matter density may fall far short of that required for closure. The mean baryon density may greatly exceed that inferred from light-element abundances. Non-gravitational processes may play a critical role in cluster formation. Standard techniques for estimating cluster masses may be grossly in error. We discuss these possibilities and conclude that neither of the last two appears plausible. If this is accepted, either the Universe has low density or the standard interpretation of element abundances is incorrect.

An inventory of the Coma cluster

We now carry out an inventory of the three main mass components in the Coma cluster: stars in galaxies, hot intracluster gas and dark matter. Present data allow determinations of the mass of each of these components out to the Abell radius. The amount of visible material is probably known to better than 30%; the amount of dark matter can only be determined to similar precision if some specific *a priori* assumption is made about the shape of its distribution.

The mass in stars. The extensive survey of Godwin and collaborators[20-22] remains the best source of photometry for the Coma cluster. After correction for background galaxies and for cluster galaxies too faint to be catalogued, these data give a total blue luminosity of $1.95 \times 10^{12}\,h^{-2}\,L_\odot$ (where $L_\odot$ is the blue luminosity of the Sun) within a circle of radius r_A. Using an analytic fit to the galaxy counts[23,24], we find the luminosity within a sphere of radius r_A to be $1.8 \times 10^{12}\,h^{-2}\,L_\odot$. To convert luminosity, L, to mass M, we take the relation $M/L = 8.0\,h\,(L/L_*)^{0.35}(M_\odot/L_\odot)$ which van der Marel[25] derived from a detailed study of 37 bright elliptical galaxies (here $L_* = 10^{10}\,h^{-2}\,L_\odot$ and $M_\odot$ is the mass of the Sun) and we average it over a luminosity function similar to that of Coma to get $\langle M/L\rangle = 6.4\,h$. This gives a total stellar mass of

$$M_{gal} = 1.0 \pm 0.2 \times 10^{13}\,h^{-1}\,M_\odot \qquad (1)$$

where the uncertainty corresponds to a 0.2 mag uncertainty in the photometry, but neglects possible systematic errors in galaxy mass estimates.

The mass in hot gas. The most accurate determination of the mass in X-ray emitting gas in the Coma cluster comes from the Rosat all-sky survey data. Briel *et al.*[26] measured the X-ray surface brightness profile of the cluster to radii well beyond r_A. After trying a wide range of possible shapes for the binding mass profile (each requiring a different gas temperature profile to be in equilibrium and to fit the mean cluster spectrum) they concluded that the gas mass within $2.5\,h^{-1}$ Mpc lies in the range $M_{gas} = 9.0 \pm 2.6 \times 10^{13}\,h^{-5/2}\,M_\odot$. At the Abell radius, the surface brightness is still well determined, with an uncertainty of just ±15%. Scaling the gas mass of Briel *et al.* to this radius using their analytic fit to the surface brightness profile, we find

$$M_{gas} = 5.45 \pm 0.98 \times 10^{13}\,h^{-5/2}\,M_\odot \qquad (2)$$

where we adopt a 15% uncertainty in the Rosat flux and a 10% uncertainty in the conversion from flux to gas mass due to the unknown temperature at large radii. Note that ±2 standard deviations (s.d.) agrees with the total allowed percentage variation quoted by Briel *et al.*

The dark mass. The total mass within the Abell radius may be estimated independently from optical and from X-ray data. All estimates begin by assuming that the cluster is spherical and in dynamical equilibrium. Optical data constrain the mass strongly only if some assumption is made about the relative distributions of galaxies and of dark matter; for example that the galaxies may be treated as randomly chosen mass elements (the 'light traces mass' assumption). Similarly, in the absence of temperature information at large radii, the X-ray data constrain the mass strongly only if some shape is assumed for the density profile (or equivalently for the temperature profile). Dynamical simulations of cluster formation can eliminate some of these uncertainties; when studying any specific picture for the origin of structure it is reasonable to assume that the density profiles of real clusters are similar in shape to those of simulated clusters.

Comprehensive virial analyses of the optical data on Coma[24,27] show that if the form of the mass distribution is unconstrained, then the velocity dispersion and number density profiles are consistent with total masses (M_{tot}) within r_A ranging a factor of 2 on either side of the central value, $6.6 \times 10^{14}\,h^{-1}\,M_\odot$. But if it is assumed that light traces mass, this quantity is determined to better than 30%:

$$M_{tot} = 6.7 \pm 1.0 \times 10^{14}\,h^{-1}\,M_\odot \qquad (3)$$

where we take The and White's total allowed range[24] to correspond to ±2 s.d.

The mass cannot be estimated from the X-ray data directly because there is no reliable temperature information beyond $r_A/3$. In the most thorough analysis to date, Hughes[28] finds weak evidence that the gas temperature falls outside the central region (see also ref. 29) and he prefers a model in which the optical light traces the mass. For such a model the X-ray data give a very precise determination of the mass, with a total allowed range of ±13% according to Hughes. Using an analytic fit to the galaxy counts[24] to convert Hughes's quoted masses to a value within r_A, we find

$$M_{tot} = 6.82 \pm 0.34 \times 10^{14}\,h^{-1}\,M_\odot \qquad (4)$$

where we have taken Hughes's 99% confidence interval to correspond to ±2.6 s.d. Note the excellent agreement between equations (3) and (4).

The cluster mass profiles found in N-body simulations do not, in general, have the shape implied by the light traces mass assumption. If we assume that real cluster mass profiles have the shape expected in a specific cosmogony, different mass estimates usually result. For simulated clusters we can ask: for what mass would a galaxy population with the observed spatial distribution have the observed velocity dispersion? Or a gas atmosphere with the observed emission profile have the observed mean temperature? We use three sets of simulations to address this problem. All consider cold dark matter (CDM) universes with $\Omega_0 = 1$. The simulations of Frenk *et al.*[30] follow the dark matter only, whereas those of J.F.N., C.S.F. and S.D.M.W. (manuscript in preparation) and A.E.E. (manuscript in preparation) also include an adiabatic gas using the smoothed particle hydrodynamics (SPH) technique. In comparing with Coma we adopt a velocity dispersion of $970\ \mathrm{km\,s^{-1}}$ for a magnitude-limited sample of galaxies within the Abell radius[23,24] and a mean gas temperature of 7.5 keV.

The Frenk *et al.* simulations produced 152 clusters with velocity dispersions greater than $800\ \mathrm{km\,s^{-1}}$. Near the Abell radius, their mass density profiles have a slope of ~2.4, which is somewhat shallower than the slope (2.72), found for the galaxies in Coma. Thus, we reduce the measured velocity dispersions by $\sqrt{2.72/2.4} = 1.06$ to get estimated 'galaxy' velocity dispersions, $\langle v_g^2\rangle$, for the simulations. Viewing each artificial cluster along one of three orthogonal directions we can evaluate the ratio of $r_A\langle v_g^2\rangle/G$ to the mass within r_A (G is the gravitational constant). Using the mean and dispersion in this factor we estimate that in Coma the total mass is given by

$$M_{tot} = 8.5 \pm 2.6 \times 10^{14}\,h^{-1}\,M_\odot \qquad (5)$$

The scatter here is quite large and is due to departures from virial equilibrium, to asphericity, and to substructure. For this exercise cluster members were identified using full three-dimensional information. If instead they had been identified in projection, mimicking observational procedures, the inferred uncertainty would have been even larger[30].

Our gas dynamical simulations follow 12 clusters with a wide range of final temperatures. In all cases the temperature is nearly constant over the regions of the final cluster that emit most of the X-ray flux, but drops at larger radii. This agrees with the available data in Coma[28,29]. Also, the surface brightness profiles are very similar in shape to that observed. Scaling these models to a mean X-ray temperature of 7.5 keV gives a mass estimate,

$$M_{tot} = 1.10 \pm 0.18 \times 10^{15}\,h^{-1}\,M_\odot \qquad (6)$$

This is consistent with our estimate from the galaxy velocity dispersion for the same assumed profile shape, but its uncertainty is much smaller. This is because X-ray data are less susceptible to projection and contamination effects than optical data, as well as being free from uncertainties due to the unknown shape of galaxy orbits.

We have shown that estimates of the mass within the Abell radius of the Coma cluster from optical and X-ray data agree well for consistent assumptions about the shape of the mass density profile. For profiles similar to those expected in a flat CDM universe, estimated masses are about 50% larger than if light traces mass. To be conservative, and because this is indeed the kind of model we wish to test, we will adopt the CDM estimate, $M_{tot} = 1.1 \times 10^{15}\,h^{-1}\,M_\odot$. We assume a 1 s.d. uncertainty of ±20%, slightly larger than the scatter estimated from our relatively small set of simulations.

The baryon fraction. Collecting these results, we find that in the Coma cluster the baryon fraction within the Abell radius is

$$\frac{M_b}{M_{tot}} \geqslant 0.009 + 0.050\,h^{-3/2} \qquad (7)$$

where the first term comes from the galaxies and the second from the gas. The inequality reflects the fact that some of the dark matter may be baryonic. The uncertainty in the right-hand side is about 25% for our adopted uncertainties in the observational mass estimates. This ratio must be compared with the value, $\Omega_b = 0.0125\,h^{-2}$, predicted by cosmic nucleosynthesis. The difference is a factor of 4.7 for $h=1$, and a factor of 3.0 for $h=0.5$. Notice also that the gas mass exceeds the galactic mass by a factor of 5.6 for $h=1$, and by a factor of 16 for $h=0.5$. Although we have focused on the Coma cluster, the available data for other rich clusters suggest that Coma is quite typical (for example, ref. 19).

Maximal baryon infall

We now estimate the maximum baryon enhancement that can be produced by dissipative effects during cluster formation. This upper limit will be a decreasing function of distance from the cluster centre; within a sufficiently large radius the mean baryon fraction must take the global value. Existing simulations suggest that hydrodynamical effects have little influence on, and may even decrease, the baryon fraction within the Abell radius[31–33]. To provide a conservative limit we consider (unrealistic) models in which pressure is never able to support the gas against collapse. We first analyse spherical models, and then check their applicability by direct simulation of cluster formation in a CDM universe.

Self-similar accretion. A simple model for cluster formation follows a spherical perturbation in an otherwise uniform universe. Each shell of matter expands to a maximum radius, turns around, falls back, and then settles to equilibrium in the main body of the cluster. For accretion onto a point mass embedded in an Einstein–de Sitter universe, the assumption that the mean equilibrium radius of each shell is a fixed fraction of its maximum radius leads to a cluster density profile[34,35], $\rho \propto r^{-9/4}$. Bertschinger[36] derived the full solution to this problem for both collisionless and collisional fluids. In any such model there is a critical radius at which infalling matter either shocks or first meets collisionless material that has passed through the cluster centre. The mean baryon fraction within this, or any larger radius, must take the global value.

As a limiting case, we may treat the baryons as a pressureless fluid that collapses in free-fall onto a central singularity, and then sticks to it. In this case, the similarity solution in an Einstein–de Sitter universe consists of a point mass growing with time t as $t^{2/3}$ surrounded by infalling gas with density profile $\rho \propto r^{-3/2}$ at small radii[35–37]. For a universe dominated by dark matter but containing a small fraction of such infinitely dissipative 'baryons', we can calculate the baryon enhancement within any sphere by assuming the dark matter to follow the collisionless infall solution and the baryons to follow the singular or 'black hole' solution. This procedure is easily seen to be conservative for our purposes because it takes the largest possible baryon fraction within any radius, r. In the similarity solutions the radial variable is usually taken to be r/r_{ta} where $r_{ta}(t)$ is the radius of the shell which is currently turning around. But for our purposes it is more convenient to use the mean enclosed overdensity, $\Delta(r) = 2GM_{tot}(r)/H_0^2 r^3$, as we can estimate this immediately from the data presented in the last section whereas the determination of r_{ta} for Coma is quite problematic. We use the similarity solutions to express the baryon (M_b) and dark matter (M_{dm}) masses within radius r as a function of the dark matter overdensity at r/r_{ta}, and we estimate the baryon enhancement factor as $\Upsilon(\Delta) = M_b(\Delta)/\Omega_b M_{dm}(\Delta)$.

The thick dashed line in Fig. 1 shows the enhancement calculated in this way from Bertschinger's solutions[36]. Our total mass estimate for Coma implies a density contrast of 280 ± 56 within the Abell radius. The maximum possible enhancement at that density is $\Upsilon = 1.4$, a modest factor compared to that required. Factors $\Upsilon > 3$ are reached only at densities, $\Delta > 10^4$, corresponding to radii $r < r_A/5$.

3-D gas dynamic simulations. It is reasonable to be suspicious of the spherical symmetry of the similarity solutions. Hierarchical clustering models that fit the overall galaxy distribution form clusters primarily through mergers within extended filamentary structures, a process which is by no means spherically symmetric. Could this produce greater baryon enhancement than we have just estimated? We address this question by carrying out realistic simulations of cluster formation in a CDM universe, making the extreme assumption that the gas is effectively pressure-free at all times; this is expected to maximize the concentration of baryons into clusters. Previous simulation work has attempted a more realistic treatment of gas physics and has found that while cooling can lead to large baryon condensations in cluster cores, the baryon fraction within the Abell radius remains close to the global value[18,31–33,38,39].

Our simulations use a computer code that combines an N-body integrator with the SPH technique, and uses a nearest-neighbour binary tree to calculate the gravitational forces; it can thus follow the evolution of a mixture of gas and dark matter. (A full description can be found in Navarro and White[40].) Initial conditions were obtained from the N-body simulations of Frenk *et al.*[30], who modelled the growth of structure in a (360 Mpc)^3 region of an $\Omega_0 = 1$, $h = 0.5$ CDM universe. From an output time corresponding to fluctuation amplitude $\sigma_8 = 0.63$ (in the notation of ref. 30), we selected 20 clusters with one-dimensional velocity dispersions $\sigma \sim 1{,}000$ km s^{-1}. For each cluster, the particles in a sphere with overdensity 200 were traced back to the initial conditions and a cubic region containing all of them was defined. This region was then filled with 10,648 new particles on a cubic grid, which were perturbed using both the original waves of the Frenk *et al.* initial conditions and additional waves between their limit and the Nyquist frequency of the new grid. The tidal field due to mass outside this box was provided by ~6,000 particles of radially increasing mass, using a technique similar to that described by Katz and White[38]. The gas component is represented by 10,648 particles with the same initial positions and velocities as the dark matter. The gas fraction by mass is 10%, and gas outside the 'high-resolution' box is ignored.

To approximate a pressure-free collisional fluid, we adopt an isothermal equation of state with temperature $T = 10^4$ K, much smaller than the virial temperature of any resolvable structure in the simulations. This results in gas sinking to the centre of any nonlinear structure in one local free-fall time, just as in the self-similar black hole solution. The main difference in the three-dimensional case is that at early times gas concentrates at all the separate local potential minima in the clumpy protocluster. The simulations follow the aggregation of these baryon clumps within the final cluster. We find that most of them merge into a single central clump during, or very soon after, their first pericentric passage.

In Fig. 1 we compare our final clusters with the spherical model by plotting baryon enhancement against mean overdensity, calculated within spheres. The striking result is that all the thin curves representing the simulations lie below the thick curve calculated above. The spherical-infall model solution thus provides an upper limit to the baryon enhancement possible in the inner regions of a cluster. The mergers and the strong deviations from spherical symmetry which occur during cluster formation in a CDM model cannot produce the baryon excess that we observe within the Abell radius of Coma.

Application to the Coma cluster. The ratio, Υ, of the baryon fraction in the Coma cluster to the standard nucleosynthesis value for an $\Omega_0 = 1$ universe is plotted in Fig. 1 at $\Delta = 280$. We have assumed $h = 0.5$ as any larger value would increase Υ still further; arrows indicate values for $h = 0.4$ and $h = 1$. The 'observational' point lies well above the enhancements allowed by our maximally dissipative models. We can quantify the discrepancy by means of Monte Carlo simulations. We generate random values of Υ and Δ consistent with the uncertainties in the four 'observational' quantities, M_{gal}, M_{gas}, M_{tot} and Ω_b, assuming normal distributions for Ω_b and for the logarithms of the three masses. We take standard deviations equal to the uncertainties quoted in the earlier section on the Coma cluster. We compare

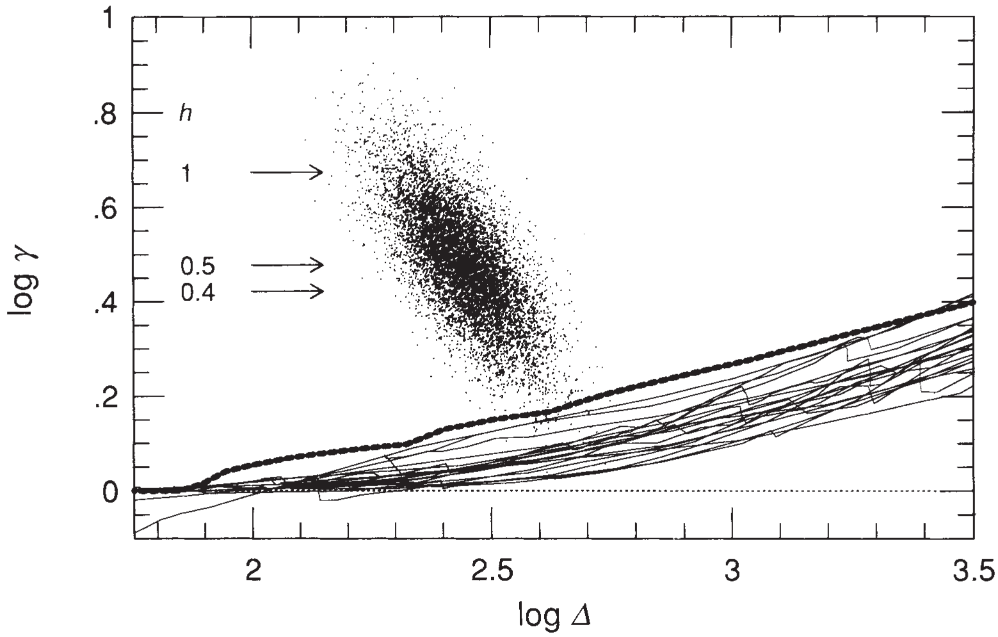

FIG. 1 The baryon overabundance (Υ) as a function of mean overdensity (Δ); note the logarithmic scales. The thick dashed curve shows the result of spherical self-similar accretion of pressureless gas in a universe dominated by collisionless dark matter. The thin curves are the results of our *N*-body-SPH simulations of pressureless accretion in clusters formed in a cold dark matter universe. The dotted line indicates models where no segregation between gas and dark matter has occurred. The dots represent 7,500 (Υ, Δ) pairs for the Coma cluster drawn at random using the uncertainties for Ω_b and for the masses of the different components quoted in the text. A Hubble constant of $50\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ has been adopted. The arrows show how the value of Υ for Coma would change for different values of the Hubble constant, given in units of $100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$.

each (Υ, Δ) pair with the enhancement curve of a randomly chosen cluster from our 20 simulations. (We plot 7,500 of these pairs as dots in Fig. 1, giving rise to the cloud of points surrounding our best estimate of Υ and Δ.) The fraction of such pairs that lies below the curves gives an estimate of the probability that the Coma measurement could be a statistical fluke arising in one of our maximally dissipative CDM models.

Of 10^5 Monte Carlo realizations, only 107 of the (Υ, Δ) pairs lie below the model curves. Our models are thus ruled out with about 99.9% confidence. Only five of the pairs give an enhancement less than unity, the typical value found in simulations using 'realistic' parameters for cooling and other dissipative processes. Such models are thus excluded much more strongly than the extreme, maximally segregated case we have considered. Our quoted confidence levels should obviously be treated with scepticism because the uncertainties on the 'observational' quantities are attempts to quantify possible systematic effects rather than true statistical errors. Nevertheless, even if we double the uncertainties quoted above, our maximally segregated model is still excluded with 95% confidence, and the unsegregated model with 98% confidence.

Discussion

The observational data indicate that a large fraction of the binding mass is baryonic in the Coma cluster. For standard values of the Hubble constant ($h=0.5$–1) this fraction exceeds the value predicted by cosmic nucleosynthesis in an $\Omega_0=1$ universe by a factor of at least three. Our principal result is that cooling and other dissipative effects cannot enhance the baryon density sufficiently to eliminate this discrepancy if clusters form by gravitational collapse. Although substantial enhancements are possible in the core of a cluster[18], our fiducial radius is only slightly smaller than the boundary that separates infalling matter from matter that is already part of the cluster. Averaged within this boundary, the baryon fraction must take the global value regardless of processes occurring at smaller radii.

What other resolutions of this discrepancy are possible? Let us now consider various possibilities.

Low-density universe. The obvious solution is that $\Omega_0<1$. A 'light traces mass' estimate for the total cluster mass seems *a priori* most appropriate in such a universe. The baryon fraction within the Abell radius is then $0.015+0.080\,h^{-3/2}$. If enhancement effects are weak we may identify this with Ω_b/Ω_0 and obtain

$$\Omega_0=0.16\,h^{-1/2}/(1+0.19\,h^{3/2}) \qquad (8)$$

when the nucleosynthesis value is used for Ω_b. This may be too large as some of the unseen matter may be baryonic. The flat universe required by the inflation model can be rescued by a non-zero cosmological constant, a possibility which has other attractive features[41] but which still conflicts with dynamical evidence for large Ω_0[3–6].

Nonstandard nucleosynthesis. Models for inhomogeneous nucleosynthesis allow some relaxation of the bounds of Walker *et al.*[1]. Such models require very carefully tuned parameters in the physics of the quark–hadron phase transition, and the kind of phase transition required currently seems rather unlikely.[42]

Nongravitational effects. Another possibility is that non-gravitational processes concentrate baryons in clusters. Unfortunately, whereas it is relatively easy to think of reasons why baryons might be under-represented (for example, energy injection by galaxies might lead to gas being blown out) the reverse seems much less likely. If structure on large scales were produced by explosive processes[43,44], clusters might form first in baryons and only later accrete dark matter. However, limits on the Compton distortion of the microwave background seem to rule out such models conclusively[45]. One might also imagine a model in which some fraction of the dark matter is kept out of rich clusters by its large random motions. For such models to be consistent with other data, the fraction of the dark matter which is 'hot' cannot exceed 30% (ref. 46), so the discrepancy in baryon fraction could be reduced only by a similar factor.

Mass uncertainties. In our earlier discussion of the Coma cluster, we identified several sources of systematic uncertainty in the masses, and we attempted to quantify their magnitude. In particular, we used numerical simulations to estimate how lack of symmetry, nonequilibrium and projection effects, and the unknown shape of the mass density profile can affect our derived total masses. These effects are serious, particularly when using optical data, but they seem too small to explain the discrepancy. A further complication is the possibility that the gas may be locally inhomogeneous. Let us define a clumping factor, $f=\langle\rho_g^2\rangle/\langle\rho_g\rangle^2$, where ρ_g is the gas density and the averages are taken over all the gas in some local volume. For fixed X-ray luminosity, X-ray temperature, and for uniform pressure within this volume, the mean gas density and the pressure p scale approximately as $\langle \rho_g \rangle \propto f^{-1/2}$ and $p \propto f^{1/2}$ respectively. Thus, for given X-ray data, clumping reduces estimates of the gas mass by roughly $f^{-1/2}$. It also affects estimates of the total mass. If the dense regions that dominate the observed emission are strongly coupled to the rest of the gas (for example by magnetic fields), then from the relation $M(r) = -r^2/G\langle \rho_g \rangle \, dp/dr$, it is clear that the inferred binding mass scales roughly as f. If the dense regions move freely through the hotter gas, the X-ray data do not constrain the binding mass at all. In either case the agreement between binding mass estimates based on optical and on X-ray data becomes purely fortuitous. In addition, the Sunyaev–Zeldovich decrement[47] predicted from the X-ray data scales as $f^{1/2} h^{-1/2}$ and agrees with the observed value in Coma for $f \sim 1$ and $h \sim 0.5$ (T. Herbig, personal communication). Thus the available data support the theoretical prejudice that substantial small-scale clumping is implausible.

In conclusion, the large baryon fraction observed in clusters of galaxies may require us to abandon at least one of the basic tenets of current theories for the formation of structure in the universe. □

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Mode-switching of a voltage-gated cation channel is mediated by a protein kinase A-regulated tyrosine phosphatase

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Tyrosine kinases and tyrosine phosphatases are abundant in central nervous system tissue, yet the role of these enzymes in the modulation of neuronal excitability is unknown. Patch-clamp studies of an *Aplysia* voltage-gated cation channel now demonstrate that a tyrosine phosphatase endogenous to excised patches determines both the gating mode of the channel and the response of the channel to protein kinase A. Moreover, a switch in gating modes similar to that triggered by the phosphatase occurs at the onset of a prolonged change in the excitability of *Aplysia* bag cell neurons.

SERINE/THREONINE kinases modulate the activity of both voltage-gated and ligand-gated ion channels in a number of vertebrate and invertebrate systems[1–6]. In contrast, phosphorylation of ion channels by tyrosine kinases has been observed only for the acetylcholine receptor, a ligand-gated channel[7]. This phosphorylation seems to mediate growth-related changes in receptor localization and may be relatively permanent[8]. Thus, the role of tyrosine phosphorylation in the modulation of the activity of voltage-gated channels and neuronal signalling is unclear.

In bag cell neurons of the sea-hare, *Aplysia*, elevations in intracellular cyclic AMP trigger a depolarization that causes a roughly 30 min period of spontaneous repetitive action potentials referred to as the afterdischarge[9–12]. To characterize the mechanism underlying the onset of this spontaneous firing we studied the regulation of a voltage-gated cation channel. We now report that the effect of cAMP-dependent protein kinase (PKA) depends on the gating mode of the channel and that this mode is determined by the phosphorylation state of tyrosine residues on the cation channel or a closely associated protein.

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