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Symposium Summary

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1.1 Introduction

I will refrain from taking the normal path followed by lecturers asked to summarize conferences, who tend to emphasize three things: the physical principles behind the science, recent dramatic observational results, and, finally, a summary of their own work. The first two have been well presented by the individual lecturers, and the last is available to the interested reader on ADS. Thus, references to my own and others' papers will be kept to a minimum. Instead, I will focus on the questions (rather than the answers): those asked and those not very much addressed.

1.2 Important Results Addressed by Speakers

1.2.1 Theory on Halos

The talks by S. White, A. Evrard, B. Moore, and others amply demonstrated that, within the context of relatively standard, hierarchical dark matter dominated schemes for understanding cosmic structure formation, the calculation of certain "halo" properties is well in hand. Dark matter simulations of a specific cosmological model by different practitioners give essentially identical results—if only the gross features are analyzed. Specifically, if one takes some agreed-on density threshold to define a halo (e.g., such that the mean density within structures defined by such a contour level is 200 times the critical density of the Universe at the epoch in question) and then terms the structures so isolated "individual halos," and then one defines the distribution $dP = N_{\rm h}(M,z)dV dM$, which gives the probability that a halo of mass $M \rightarrow M + dM$ will be in dV at epoch z—this function is well understood. Good approximations abound (Press-Schechter, Sheth-Tormen), accurate N-body simulations can easily be made, and different codes/investigators will agree on the results at the 10%–20% level. But there is great uncertainty on other more detailed, closely related subjects: substructure within halos and inner halo slope are two such uncertainties. Are there well-defined subhalos within each halo, and, if so, how can they best be characterized and what is their spatial and mass distribution? This is an important question since it is primarily subhalos, not halos, that would be the homes of observable galaxies. Secondly, does the inner slope α (proportional to $r^{-\alpha}$) have a value close to 1.0, as advocated by Navarro, Frenk, & White (1996), or close to 1.5, as advocated by Moore et al. (1998), or does it have a fair dispersion, with the mean value dependent on the slope of the power spectrum (or effectively on the halo mass), as advocated by Subramanian, Cen, & Ostriker (2000) and Ricotti (2003)? The jury is out on this very important question.

1.2.2 Halos Equal Galaxies?

Second, even if we did understand the properties of the halos completely, how good would be the extremely plausible theoretical assumption—common to all the semi-analytical methods for galaxy formation—that there is a unique correspondence between halo properties and galaxy properties (cf. White and Kauffmann, this conference). Within individual observed systems, the mass distributions of the stellar and halo components are largely non-coextensive; stars and gas dominate the inner parts of galaxies and dark matter halos (if they are present) only dominate in the outer parts, where there are relatively few observational tracers. Insofar as direct numerical simulations have studied this issue, the evidence is mixed and uncertain (Cen & Ostriker 2000: note Fig. 1, galaxies without halos; but also see Yoshida et al. 2002 and Hernquist & Springel 2003: star formation rates from semi-analytical methods and direct numerical simulations agree), so at this point, we would have to say that we simply do not know if the fundamental assumption of semi-analytical methods is valid, or is a pretty good approximation, or is inadequate.

1.3 EROs

One important byproduct of a naive application of this assumption definitely appears to be wrong. While it is certainly true that low-mass dark matter halos form early and high-mass dark matter halos form late, the same does not appear to be true for galaxies. The extremely red objects ("EROs") found by R. Ellis and co-workers (this conference), A. Renzini and co-workers (this conference), and others are clearly giant ellipticals in a fairly complete state of formation seen at moderate to high redshift in numbers approaching those of local giant ellipticals; they are "old" at redshift 2–3. But, low-mass local systems, from dwarf irregulars to some dwarf spheroidals, seem to have had ongoing star formation and, in some cases, seem astrophysically young (i.e., dominated by gas and young stars). Does this invalidate the hierarchical structure formation scenario? I think not. But it does invalidate the simpler versions of semi-analytical methods. In the hydro simulations (e.g., Nagamine et al. 2001, Fig. 3), low-mass galaxies do start forming first, but in the high-density regions, they rapidly merge to make massive systems; and then further infall and star formation ceases (Butcher-Oemler and Dressler-Gunn effects), since they find themselves surrounded by hot gas, which is unable to cool or accrete onto the formed galaxies. But in lower-density regions the dwarf systems survive and continue to accrete gas with ongoing intermittent and inefficient bursts of star formation. Thus, the surviving examples of massive systems are old, and the surviving examples of low-mass systems are relatively young. But, clearly, much more observational and theoretical work will need to be done to test if this proposal is correct or if the existence of EROs does pose a challenge to the ΛCDM paradigm.

1.3.1 Feedback

M. Norman and co-workers (this conference), L. Hernquist and co-workers, and others have wrestled with how to include the "feedback" from star and galaxy formation onto the subsequent star and galaxy formation. One aspect of this problem is well understood and, if not solved, at least on its way to solution. The output of ionizing (and hence heating) radiation from stars, accreting black holes, supernova remnants, etc., is vitally important in reheating and reionizing the Universe and provides, globally, the thermodynamic context for galaxy formation. This is already included in the hydrodynamic codes. Locally, where we should make appropriate allowance for individual sources and sinks of radiation, we know what to do, but are only gradually implementing the detailed radiative transfer required to do it right (cf., for example, Cen 2002; Razoumov et al. 2002). Observations provide strong guidance here, since we can actually see in the UV the relevant radiation from galaxies and can thus make sure that our theoretical modeling is accurate. But perhaps equally important is the mechanical energy input into the intergalactic medium from supernovae (collectively galactic winds and "superwinds") and jets from AGNs. We observe (cf. Heckman and co-workers; e.g., Cid Fernandes et al. 2001) the outpouring of mechanical energy from nearby starburst galaxies and Steidel and Adelberger (this conference) have found that this is generically present in the Lyman-break galaxies at redshifts $z = 2-3$. How does one model this physical process, and is it important in affecting further galaxy formation? The answer, simply put, is that we do not presently know how to model it and we believe that it is important. The difficulty is that most of the relevant codes do not include magnetic fields or cosmic rays, nor do they allow for the consequent multiphase medium induced when supernova energy is injected into such a medium (cf. Cox 1979; McKee & Ostriker 1988). In such a medium, where most of the gaseous mass is contained in "clouds" or "filaments" occupying a small fraction of the volume, blast waves will propagate efficiently through the low-density component and can emerge from a galaxy with only moderate losses. But accurate computation with current generation high-resolution codes (e.g., Gnedin & Bertschinger 1996), which do not allow for the high-energy component and consequently do not generate multiphase media, simply find that the supernova blasts are radiatively quenched. One solution to the problem (Yoshida, Sugiyama, & Hernquist 2003) is to put a plausible multiphase medium into the codes "by hand," while another (Cen & Ostriker 2004) is to bypass the difficult problem of propagation of blasts within a galaxy by injecting the energy in the volume surrounding the galaxy and normalizing the energy output by observations of starburst galaxies and Lyman-break galaxies. It is not known now if either of these approaches will be satisfactory.

1.3.2 Clusters Gas Cooling Problem

Many authors (e.g., R. Mushotzky, M. Norman, and others, all at this conference) have stressed that we see gas in clusters of galaxies that has a radiative cooling time shorter than the Hubble time, but the gas does not seem to be cooling and "dropping out" as stars. How is one to understand this? This is a real and important point, but it is necessary to stress that this is also true for almost all other gas in the Universe. It is true for the general intergalactic medium (not just the cluster gas); it is also true for the general interstellar medium (where star formation on a cooling timescale is less than one part per thousand); and it is true for the gas in the Sun! But, in all these other venues, we know the explanation; there exists some heating process, either steady or intermittent, which balances—in a time averaged sense—the inevitable (and observed) radiative cooling. We remain uncertain what that process is in the clusters of galaxies, with the best guess to date (cf. Binney and co-workers; e.g., Binney & Tabor 1995) being mechanical energy input from AGNs. This problem (and its solution) is probably related to the problem that the cluster temperature-luminosity relation is not as expected theoretically, a mystery pointed out by several lecturers at this conference.

1.3.3 Cluster Star Formation Rates

A. Renzini, A. Dressler, and others at this conference have stressed that the star formation rate is not highest in the highest-density regions. A simple application of "bias" would say that galaxy density monotonically increases with dark matter density (in the simplest picture increases linearly), and so, dividing by the Hubble time, we should find the highest rates of star formation in the richest clusters. But, the contrary is correct: star formation rates are unusually low in such regions! Why? Over the years, physical collisions, ram pressure stripping, and tidal shocks have been proposed as mechanisms to explain this phenomenon. All must occur and must contribute to the solution, but surely the root cause is that the escape velocity from typical galaxies is less than the rms velocity of galaxies in clusters, or (equivalently) the speed of sound in the cluster gas. Thus, energetically, there is simply no incentive for gas to settle in or to stay in galaxy potential wells for galaxies in rich clusters. To date, semi-analytical models, which tend to treat the "halo" as the unit that fixes the properties of the hypothetically embedded galaxy, have not easily included the interaction between a forming galaxy and the surrounding intergalactic medium. But the hydro methods (cf. Blanton et al. 2000, Fig. 12) naturally reproduce the Butcher-Oemler and Dressler-Gunn effects.

1.4 Observations, Phenomenology, and Data Interpretation

There appears to be a universal agreement (cf. W. Couch, C. Miller, R. Nichol, and others at this conference) concerning the star formation rate at the other extreme—regions of low stellar density. At low redshift, the star formation rate decreases rapidly as the stellar density decreases. We know of this as an empirical result, valid if we average over regions with a smoothing length measured in kiloparsecs or megaparsecs. We do not understand the cause of this phenomenon, and it would be most helpful if it could be quantified better by the observers. The relation cannot be true at all epochs or otherwise galaxy formation could never have commenced (since at early time $\rho_* \to 0$ everywhere)! I suspect that the critical variable is, in fact, gas density, not star density, and that at the current epoch most regions of low stellar density also have a low density of cold gas, but that at earlier epochs, galaxy formation was initiated in regions of low stellar density, which had a high density of dark matter and of gas. In general, both observations and theory indicate that if there are regions within which the gas density dominates over both the stellar and dark matter densities, and both cooling and Jeans criteria are satisfied, then star formation is prompt.

1.4.1 High-density Regions

J. Huchra, R. Mushotzky, R. Davies, B. Poggianti, A. Renzini, L. Jones, T. Treu, M. Franx, D. Kelson, A. Dressler, and others at this conference agree that, in high-density regions (e.g., clusters of galaxies), galaxies are brighter, older, and perhaps somewhat more metal rich than in lower-density regions. In fact, if the giant ellipticals formed at redshifts $z \gtrsim 2.5$, then the circumambient gas must have been enriched in metals even before the clusters formed. It is an open question if these important facts, which are universally agreed on by observers, are consistent with the current standard $\Omega_{\rm m} = 0.3$ ΛCDM models. My own guess is that they will force us to consider lower-density models (e.g., $\Omega_{\rm m} = 0.2$), within which galaxy formation commences earlier than in $\Omega_{\rm m} = 0.3$ models.

1.4.2 X-ray Cluster Evolution

The closely related finding (cf. P. Rosati, B. Holden, and others at this conference) that the X-ray clusters have evolved relatively little from the present back to $z \approx 1$ provides an interesting and important puzzle. This is likely to be another strong indicator that we live in a low-density Universe (cf. N. Bahcall and co-workers).

1.4.3 Internal X-ray Cluster Structure

R. Mushotzky, M. Donahue, A. Renzini, and others at this conference have stressed that in the "X-ray concentrated" clusters, the central cores are higher in density, lower in temperature, and higher in metallicity than the other parts [$T_c \approx (1/3)\langle T \rangle$]. But these are not cooling flow clusters, since the absence of still lower-temperature gas shows that the expected cooling flows are not occurring. This presents, as noted earlier, a set of serious theoretical puzzles. What keeps the gas in such regions from fragmenting and from collapsing further to higher densities and lower temperatures?

1.5 Methodology and Technology

1.5.1 Weak and Strong Gravitational Lenses

Several authors (e.g., J. Cohen, I. Smail, M. Postman, and others at this conference) have stressed the potential of techniques to measure the distortion or multiplication of galactic images due to the effects of intervening gravitational inhomogeneities. These techniques, still in their infancy, have enormously powerful potential in that they measure directly the gravitational field perturbations along the line of sight, and are thus unaffected by our insecurity in understanding the complicated relations between mass and light distributions. Preliminary results obtained are roughly consistent with those obtained by other methods. For weak lensing, improvements will be made as one is better able to accurately correct for instrumental effects in measuring low-level light distortions; for strong lensing, we await complete optical surveys with well-defined selection criteria (e.g., similar to the radio CLASS survey). Since strong lensing is dependent on the very small fraction (of order 1%–3%) of matter in the highest-density regions (on the Gaussian tail of the cosmic spectrum of fluctuations), it is very sensitive to cosmic model variations.

1.5.2 Sunyaev-Zel'dovich Effects

Similarly, M. Birkinshaw, K. Romer, and others at this conference have stressed the exciting potential of future Sunyaev-Zel'dovich surveys. This well-understood physical effect can now be used to study large numbers of clusters containing hot gas. It is linear in the integrated surface pressure, and detectability is independent of distance for resolved sources. Interpretation will require high-precision theoretical modeling.

1.5.3 Multi-band, Large-area, Deep Photometry (with Spectroscopic Follow-up)

Work by C. Steidel and co-workers (reported at this conference) and by other groups has already given us more information on galaxy formation at $z \approx 2-3$ than any other method. These techniques are still under development, but already they have provided us with vital information on the formation of galactic bulges, on the QSO-galaxy relation, on the prevalence of galactic wind feedback, etc. With additional large telescopes having large-area detectors coming online, this approach holds great promise.

1.6 Important Results Based on Clusters Not Addressed

1.6.1 Cosmology

One can guess that the primary reason that using clusters as a tool to study cosmology was not addressed specifically at this conference is that there was another Carnegie Symposium on cosmology. But it is worth stressing that both the classical cosmological parameters ($\Omega_{\rm m}$, H_0, q_0) and the newer ones (Ω_Λ, $\Omega_{\rm b}$, σ_8) are measurable using well-defined cluster samples. As an important example, Peebles and, separately, N. Bahcall have used clusters to estimate $\Omega_{\rm m}$. Essentially, one uses the virial theorem (in a manner similar to that pioneered by F. Zwicky) to estimate the total mass within a fiducial radius in a rich cluster, and observes the light from the same region. Then, the so derived mass-to-light ratio can be multiplied by the light density of the Universe to provide an estimate of the global matter density. The result is $\Omega_{\rm m} = 0.12 - 0.20$, somewhat below the estimates obtained by other modern techniques, but not obviously in error. Resolving this discrepancy is an important task. The Hubble constant can be estimated (for a given cosmological model) by combining the distance independent Sunyaev-Zel'dovich measurements with X-ray fluxes, which are inversely proportional to the square of the luminosity distance. When large samples are available (to average over projection effects), this should provide an important independent method for estimating H_0. The number density of rich clusters is a strong function of $\sigma_8\Omega_{\rm m}^{0.6}$ and therefore provides a significant constraint on the matter density perturbations at scales smaller than those directly measured by cosmic background radiation probes. But the evolution of the cluster number density is more sensitive to ($\Omega_{\rm m}$, Ω_Λ), and thus the combination of observations at a range of redshifts can significantly constrain the possible cosmological models (cf. Bahcall & Bode 2003). The lecturers S. White, M. Birkinshaw, M. Postman, and others at this conference did note the important cosmological implications of cluster measurements, but it is worth stressing that in terms of cosmic scale studied and cosmic epoch, cluster measurements are complementary to cosmic background radiation probes and thus help to remove or reduce the serious degeneracies still present even after analysis of exquisitely accurate cosmic background radiation data (cf. Bridle et al. 2003).

1.7 Discussion

I will not attempt to summarize the lively discussion section that concluded the meeting. Rather, I would prefer to emphasize my agreement with the mood of optimism. While these are among the largest and longest studied cosmological objects, the potential they provide for helping us unravel nature's secrets remains enormous. The current combination of new and much more powerful observational techniques with a well-defined theoretical paradigm for the growth of structure and, lastly, increasingly powerful computational simulations to link observations and theory will surely lead to a very rapid expansion of our understanding. I would guess that the next half century will be at least as productive as the half century that followed Zwicky's pioneering work.

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