1 Introduction

In his introductory historical review, Biviano provided a very thorough precis of previous studies of the Coma cluster stretching back to the beginning of this century and forward to the last couple of years (gracefully allowing the protagonists present at the meeting to present their own versions of the most recent work). He quantified Coma’s well-established position in the astronomical literature as the archetypal rich cluster, finding that papers on Coma represent about 5% of all papers on clusters of galaxies. He also emphasised that the last decade has seen an acceleration in the number of papers on Coma published per year. This renewed interest in the Coma cluster is reflected in the number of people attending this conference and in the extraordinary breadth of the research with Coma as its focus that was reported here. The current vitality of cluster studies seems to be based in part on technological advances which have produced high quality data at wavelengths outside the visible and led to a far fuller and richer picture of galaxy clusters, and in part on renewed interest in clusters as structured, forming entities and as laboratories for understanding galaxy formation and interaction processes in extreme density environments.

Given this history, it seems surprising that there has never previously been any conference focussed solely on Coma. This meeting has rectified that deficiency, and provided an inclusive, detailed and up-to-date snapshot of research on Coma which will serve as an invaluable source-book and inspiration for future work. In this summary I attempt to draw together a few of the highlights and major themes of the conference.
2 Substructure and Superstructure

The review by West of the Coma cluster in relation to its large-scale environs offered a view from the top of a bottom-up universe. He stressed the observational evidence for strong cross-talk between structures over a range of $10^4$ in size, from individual galaxies on scales of 10 kpc, through clusters with sizes of order 1 Mpc, up to ‘Great Filaments’ extending as much as 100 Mpc. His theme was that “filaments drive cluster formation”, and he was able to show impressive evidence for this view, including the remarkable alignment of structures on all scales: the optical isophotes of the dominant galaxies, the overall distributions of cluster galaxies and X-ray gas, and the great chain of galaxies extending across the sky, passing through both Coma and Abell 1367, which is usually called the Great Wall (though he argued its axial ratios make that a misnomer, and it should be called the Great Filament). This evidence, West contended, meant that Coma was built by the infall of subclusters along the Great Filament.

This embedding of Coma within the surrounding superstructure has been complemented by a growing understanding of the internal substructure of the cluster. Up to the early 1980’s dynamical studies of Coma tended to emphasise the relaxed, regular nature of the cluster in order to make possible analytical attacks on the hallowed questions regarding the amount and distribution of the cluster’s dark matter, famously discovered by Zwicky (1933). The late 1980’s saw a change of view, as various pieces of evidence showed that Coma was clearly not spherically symmetric and dynamically fully relaxed. The last few years have seen further rapid progress in this direction, most notably in the deep ROSAT X-ray maps of the cluster (White et al. 1993) and dynamical analyses based on many hundreds of galaxy velocities (Colless & Dunn 1996; Biviano et al. 1996).

With cluster structure now confirmed and quantified, the emphasis is switching to understanding the irregular dynamics and history of Coma’s formation. This was reflected both in West’s review and in the results presented by van Haarlem, who is measuring velocities for the galaxies in the outer parts of the cluster to obtain a fuller picture of the anisotropic infall onto the cluster. Other relevant new results in this area were presented by Gerbal, Slezak and Gurzadyan. Gerbal and Slezak both presented wavelet analyses of cluster substructure and showed that the bright galaxies in the cluster core form two tight groups around the the two dominant galaxies, NGC 4874 and NGC 4889; however the fainter galaxies are centred in-between, and are more smoothly distributed over the cluster. Gerbal and Gurzadyan presented different methods for decomposing the cluster into a hierarchy of dy-
namically significant sub-units, the former using a binding energy criterion, the latter using Riemann curvature to quantify the boundness of orbits in phase space. These investigations confirmed that the group of galaxies around NGC 4889 is undergoing disruption as suggested by Colless & Dunn (1996), but, in a modification of that picture, envisage the main cluster being traced by the fainter galaxies, with NGC 4874 and its associated bright galaxies another embedded subcluster. On the question of whether the dominant galaxies are a bound pair, however, the two analyses disagreed.

One issue that was repeatedly raised during the conference was whether the subcluster around the cD galaxy NGC 4839, lying 40 arcmin away from the cluster centre towards the south-west, has already passed through the cluster core or not. Burns et al. (1994) argued that the distribution of X-ray gas and galaxies was more consistent with a group that had been partially disrupted on a first passage through the cluster, whereas Colless & Dunn (1996) marshalled a variety of evidences pointing towards the group being on its first approach to the cluster. In fact the question of whether the NGC 4839 group has or has not already passed through the cluster core is, in itself, only of limited interest. However, that so much attention should be directed towards this question does illustrate the extent to which the primary goals for dynamical analysis of clusters have broadened from the issues of the distribution of luminous and dark matter to encompass the broader questions regarding the formation history of the cluster.

Some radio observations highly pertinent to this question were summarised at this meeting by Feretti. She showed that NGC 4839 is a wide-angled tail (WAT) radio source with the tail trailing away from the cluster centre. Since NGC 4839 appears to be at rest within its group, this implies that the WAT is produced as the group passes through the intra-cluster medium of the main cluster and hence that it is either on first approach or falling back in after having passed through the main cluster. The radio halo of the Coma cluster (an attribute seen in only 10 clusters) has a lifetime of around 0.1 Gyr, whereas the NGC 4839 group is about 1 Gyr travel-time from the cluster core. A more plausible energy source for the radio halo is thus the ongoing merger between the NGC 4874 and NGC 4889 subclusters. This is supported by the observation that the halo’s spectral index is \( \alpha \approx 0.8 \) in the centre and higher outside, implying the energy source is within the optical core radius of the cluster.

Some puzzles regarding the radio observations of Coma remain, however. The mechanism by which the kinetic energy of a subcluster merger is converted into the luminosity of the radio halo remains unclear; since such halos are rare yet subcluster mergers seem relatively common, perhaps special conditions are
required. The origin of the apparent bridge between the halo and NGC 4839 seen in the radio map of Deiss et al. (1997) is not known; it cannot be due to the passage of that subcluster since again the timescale is wrong. Finally there is the intriguing extended radio source 1253+275, which lies along the NGC 4874/NGC 4839 axis but half as far again from the cluster centre.

3 The Properties of Galaxies in Coma

Even more strongly than the dynamical analyses, the work on the properties of Coma cluster galaxies showed the new impetus provided by multi-waveband studies. This was exemplified in the review by GAVAZZI, who explored a wide range of galaxy properties, comparing cluster galaxies to field galaxies, using radio, HI, CO, far-infrared, near-infrared, optical and ultraviolet data. An even wider range of galaxy properties were discussed by other speakers.

Cluster membership: Looking beyond the cluster core, GAVAZZI noted that HI deficiency is a good indicator of cluster membership, and that by this criterion a large fraction of the spirals in the Coma region are cluster (or supercluster) members. BRAVO-ALFARO examined the possible HI removal mechanisms and concluded that ram-pressure stripping is likely to be dominant. On the other hand, BOSELLI noted that H$_2$ is not removed, apparently because it generally lies much deeper down the galaxy potential wells.

Luminosity functions: Several speakers showed new data on the cluster luminosity function (LF), both in the optical (GAVAZZI, LOBO, SEKIGUCHI, DE PRORIS) and the near infrared (GAVAZZI, DE PRORIS). In the optical there now seems to be agreement that there are three LF regimes: (1) galaxies brighter than $L^*$ occupy an exponential tail to high luminosities; (2) sub-$L^*$ galaxies follow a power law with slope $\alpha$$\approx$−1.25 (KATGERT); while (3) dwarfs cause a steep upturn at the faint end of the LF, with power law slope somewhere in the range $−1.3>\alpha>−2$. The overall shape might be represented by either a bright-end Schechter function plus a faint-end power law or by a bright-end Gaussian plus a faint-end Schechter function. However LOBO noted (as in some previous work) that the sub-$L^*$ range in Coma shows a significant bump and dip rather than a simple power-law. SEKIGUCHI examined the LF variations with radius within Coma and concluded that the faint-end (‘dwarf’) LF steepened from $\alpha$≈−1.5 in the cluster core to $\alpha$≈−1.9 beyond one Abell radius, a result consistent with the dwarf ‘deficit’ noted in the core by LOBO.

Comparing the optical cluster LF with the field LF in each of these regimes shows that: (1) at the bright end the LFs are similar except for the presence of D/eD galaxies in some clusters and (perhaps) a slightly brighter $L^*$; (2) the sub-$L^*$ LFs are also similar, though clusters show a somewhat steeper slope
than the field, at \( \alpha \approx -1.25 \) rather than \( \alpha \approx -1.0 \); (3) the very faint end of the LFs cannot really be compared since this regime is effectively unmeasured in the field due to the very small volumes encompassed by magnitude-selected samples at these luminosities. Large and/or deep redshift surveys may help here (such as the Sloan or 2dF wide-angle surveys or the deep survey reported in the poster by Adam), but it will require much work to accurately pin down the LF fainter than \( M^* + 4 \).

Consideration of the near-infrared (NIR) LF is motivated by the observation that the H or K band luminosity is the best estimator of stellar mass (Gavazzi, De Propris). In fact the H band LF has a similar overall shape to the optical LF, implying that the faint end of the optical LF is not entirely due to elevated star-formation amongst dwarf galaxies—there really are lots of low-mass galaxies, though they tend to be blue. The H band LFs in the cluster and the field are similar, at least within the current measurement uncertainties.

**Colour–magnitude relation:** Secker presented a \( B-R \) vs R colour–magnitude (CM) diagram which shows that the standard CM relation extends all the way down to \( M_R \approx -13 \). Like Lobo and Sekiguchi, he noted the deficit of faint dE’s in the cluster core. Terlevich noted a small dependence of the zeropoint of the \( U-V \) CM relation on cluster radius, with the core having a zeropoint \( \sim 0.1 \) mag redder than the periphery. Although this could possibly be due to different star-formation histories or a variation in the cluster dust content with radius, it may simply reflect the morphology–density relation, since De Propris found slightly different CM relations for E’s and S0’s (with the E’s, more common in the core, having a flatter relation than S0’s, which dominate the CM relation at larger radii).

**Morphology and environment:** Andreon raised the interesting question of whether morphological segregation is primarily based on a privileged cluster direction or axis rather than density or clustocentric radius. He pointed to the highly elongated distribution of early-type galaxies in the cluster running along the axis through the two central dominant galaxies, as previously emphasised by West. In contrast the spirals show a far more diffuse and isotropic distribution. This difference was also noted by Nichol in comparing the distributions of the reddest and bluest galaxies in the cluster. Is the formation of early-type galaxies more common either in subclusters or subcluster mergers, so that the early types show a kinematic echo of the orbits of their parent subclusters?

**Fundamental Plane:** Mobasher showed some very striking results based on his study of the near-infrared fundamental plane (FP). One of the main motivations for using the NIR FP is that it should be less subject to variations in star-formation history since the NIR light is dominated by the
old stellar population. For this reason his K-band FP is puzzling in two respects: firstly, he finds a slope $\log D/\log \sigma$ of 1.2, which is even further from the virial theorem slope of 2 than the optical FP (for which the slope is $\sim 1.4$) and disagrees with the K-band slope of 1.7 found by Pahre & Djorgovski (1997); secondly, his NIR FP has virtually identical scatter to the optical FP, when it might be expected to be less. Setting aside these issues, however, Mobasher finds a quite startling difference in the NIR FPs he obtains for Coma and the Great Attractor (GA) region, with the GA ellipticals having diameters which are 10–20\% smaller at fixed velocity dispersion. If correct, this would significantly reduce the Local Group infall into the GA; however it would also imply large variations in galaxy properties correlated on scales of at least tens of Mpc. So we have a choice: either large-scale coherent flow or large-scale correlated variations in galaxy formation! Since Pahre & Djorgovski (1997) do not see such large variations in the NIR FP in comparing different clusters, it is clearly essential to confirm these preliminary results.

**Ages and Metallicities:** Mehlert has performed spectroscopy on 35 early-type galaxies in Coma which she has used to investigate the ages and metallicities of this population, and also correlations of metallicity with galaxy luminosity and radius. Within the framework (and to the accuracy) provided by the models of Worthey (1994), she was able to conclude that the E’s are all old (>8 Gyr), while the S0’s have a wide range of effective ages. Intriguingly, the two central dominant galaxies have higher metallicities than the S0’s but lower effective ages than the E’s. This type of analysis could prove very revealing if the models can be shown to be reliable—for example, the models need to account for the over-abundance of Mg compared to Fe, and to explain why more massive E’s have a greater over-abundance than less massive E’s. Another, perhaps related, challenge for models of elliptical galaxy formation is to reproduce the observed radial metallicity gradients and account for why steeper gradients are found for more massive galaxies.

**The Butcher-Oemler Effect:** Caldwell and Rose presented the results of studies into the origin of the Butcher-Oemler (BO) effect and the nature of post-starburst (PSB) galaxies in Coma and other nearby clusters. First, they confirm using diagnostic spectral lines that PSB galaxies have indeed undergone a burst of star-formation and are not simply the result of truncating a previously constant star-formation rate. Secondly, they do not find evidence that PSB galaxies are the result of pairwise interactions—they speculated that the trigger may instead be global tidal effects induced either by infall onto the cluster or by subcluster mergers. An important question was raised by both Jones and van Haarlem: is infall onto the cluster dominated by single galaxies or by bound groups?
4 Simulations

The question that must be asked of the growing hordes simulating every possible astrophysical process and situation is: How virtual is your reality? Are the simulations (as we hope) leading to new physical insights and revealing the outcomes of processes too complicated to follow analytically? There are two opposite sorts of problems commonly encountered: either the simulations, for whatever reason, fail to adequately reflect reality (they are too ‘virtual’), or they require so much calibration from observation that they have no option but to reflect their empirical inputs (they are forcibly constrained to be ‘real’). A ‘good’ simulation is as virtual as possible (has few calibrating empirical inputs) while remaining as close as possible to reality.

In his review, EVRARD pointed to the very significant increase in the sophistication and reliability of the current generation of cluster simulations, in particular the advance from purely N-body gravitational simulations of the mass (dark matter halos) to simulations incorporating not only the gas dynamics but also preliminary recipes for star formation and other messy galaxy processes. He suggested that in fact we have reached, or even passed, the break-even point where the observational input is exceeded by the predictive output. Although the simulations at this level have yet to mature, he listed some results that he felt were robust, including: (i) galaxies at $r < r_{200}$ are in virial equilibrium ($\rho/\rho_{\text{crit}}=200$ at $r_{200}$); (ii) the velocity anisotropy $\beta$ is nearly zero at $0.1 r_{200}$ and increases to 0.5 at $r_{200}$; (iii) velocity bias is small – $\sigma_{\text{gal}}/\sigma_{\text{DM}} \approx 0.75$.

Evrard presented two other interesting results relating to the baryon fraction and $\Omega$. First, from a sample of 19 clusters including Coma, he derives a typical gas mass fraction within $r_{500}$ of $(0.06 \pm 0.03)h^{-3/2}$, implying either that $\Omega_M h^{2/3}=0.07–0.28$ (for low to high D/H ratio), or that we don’t understand Big Bang nucleosynthesis. Second, a method which compares the mass density contrast $\delta_C$ (from $TX$) and the galaxy density contrast $\delta_N$ (from galaxy counts) gives $\Omega_0/h_{\text{cluster}} = \delta_C/\delta_N \sim 0.3$, similar to the estimate obtained from the standard optical $M/L$ ratios for clusters.

VAN KAMPEN presented a summary of the techniques for constrained random field realizations of specific clusters. These methods are in their infancy as yet, but hold out the tempting prospect of a direct simulation attack on the merger histories and perhaps even (if star formation can be modelled reliably) the galaxy properties of specific clusters.

Descending in scale from simulations of rich clusters to simulations of small groups, ATHANASSOULA showed the results of some investigations aimed at understanding the processes and initial conditions which lead to the formation
of dominant brightest cluster galaxies (BCGs). While no inevitable sequence emerges from what is a necessarily stochastic process, some interesting heuristic rules seem to apply: (i) a BCG nearly always forms in poor cluster simulations unless there is nothing resembling a suitable central 'seed' concentration from which to grow; (ii) the mass in BCGs acquired by cannibalism and mergers is generally larger than (or at least comparable to) the mass acquired by accretion of material stripped from other galaxies; (iii) central concentration is a more important determinant of BCG formation than the total mass of the common halo; (iv) a cD-like extended halo is formed when accretion of stripped material is (unusually) the dominant process. In order to confront these results with observations, such simulations need to be combined with merger history trees for clusters in order to make predictions for the properties of BCGs as a function of cluster properties such as mass/richness and degree of substructure.

5 Hot Gas, Warm Gas, Cool Dust

The final session of the meeting dealt with X-ray, UV and far-infrared (FIR) observations of Coma, and demonstrated that a lot can be learnt from very few photons.

Jones summarised the now well-understood main properties of the X-ray gas, noting the greatest remaining deficiency in the observational picture is the lack of high-resolution temperature maps. In X-rays, Coma is a fairly normal massive cluster. Nonetheless, as in the optical, “the better the observations, the more substructure”. The wavelet analysis of the ROSAT X-ray image by Vikhlinin et al. (1997) shows a clear double core surrounded by a more diffuse component (in which respect it is more than reminiscent of the wavelet analyses of the galaxy distribution by Gerbal and Slezak discussed above). It also shows a distinct tail trailing from NGC 4911 towards the cluster core. A preliminary temperature map of the core is very messy (as expected from the simulations) and hard to interpret. Interestingly, the NGC 4839 group has a high X-ray temperature for its velocity dispersion, such as is also seen in the merging Centaurus clusters.

Temperature maps of the whole cluster out to about 1 degree from the centre were shown by both Briel and Honda. While these maps have very low spatial resolution (tens of arcmin) and are clearly only a first step, nonetheless the two maps did show broad agreement in their main features. Briel noted that the gas is hot between the cluster core and the NGC 4839 group, while Honda emphasised a decreasing temperature gradient from the NW to the SE of the cluster.
An update on mass estimates for Coma was given by Hughes, based on improved X-ray and optical data and modelling. He finds that the gas (and perhaps also the galaxies) have a more extended distribution than the dark matter. For $h=0.5$, the mass inside 1.3,5Mpc is in the range 5–7.8–19.10–27×10^{14}\text{M}_\odot$ (the inner two estimates are considered reliable, while the outer one is more uncertain). The baryon fraction, estimated inside 1.3Mpc is 13–17%,18–43%.

Dropping in temperature from the X-ray to the UV, Lieu presented a very careful case for the existence of a significant amount of sub-10^6 K gas in a number of clusters. In Coma, the EUVE satellite detects emission in the 50–190Å band out to 15arcmin from the cluster centre. This represents an excess over the flux predicted from the 8keV X-ray gas. Lieu claims that a three-phase model is needed, with gas at temperatures of 8keV, 0.3keV and 0.07keV. The latter component has a cooling time of only $\sim$1Gyr, so that $10^{14}\text{M}_\odot$ should have cooled out over a Hubble time—where has this material gone?

Descending even further in temperature, Stickel reported the first direct detection of dust in a cluster—the ISOPHOT instrument on the ISO satellite detects the signal of dust with a temperature of $\sim$30K in Coma. The mass involved is only $10^8\text{M}_\odot$, consistent with previous upper limits on the dust content of the cluster. The gas/dust ratio is low compared to the Galaxy, yet since the dust would be destroyed by sputtering in $\sim$0.1Gyr it is not primordial, perhaps resulting from galactic winds or stripping of the ISM.

6 In Sum

I have been inspired, intrigued and enthused by so much I have heard during this conference. I offer my thanks, and the thanks of all the participants, to Alain Mazure, Florence Durret, Daniel Gerbal and Fabienne Casoli for organising this most successful meeting, and to the various institutions and organisations which sponsored it.

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