Mon. Not. R. astr. Soc. (1977) 180, 207–218

Photoelectric surface photometry of the Coma cluster

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Received 1977 February 7; in original form 1976 October 27.

Summary. We present photoelectric observations at two wavelengths of the surface brightness distribution over a large area of the Coma cluster. The distribution of cluster light is found to follow the distribution of galaxies very closely, and there is little luminosity outside the V_{25} isophotes of the galaxies. The present data alone give an upper limit of 25 per cent for the amount of the total cluster luminosity which might come from a smoothly distributed intergalactic medium.

1 Introduction

The 'missing mass problem' in the Coma cluster has bedevilled astronomy for many years since it was first pointed out by Zwicky (1933). The dynamically determined mass of the cluster seems to be an order of magnitude larger than the sum of the masses of its constituent galaxies so that some kind of unseen material is needed to hold it together (see, e.g. Rood *et al.* 1972). Recent dynamical results (White 1976a, 1977) show that this material cannot be attached to the individual galaxies in proportion to their luminosities, and so is most probably present as a smooth intergalactic background. Absolute surface photometry of the cluster therefore promises not only to give its mass-to-*total light* ratio, but also to put limits on the surface brightness between galaxies and thereby restrict the possible luminosity of any intergalactic background. Previous photoelectric surface photometry of the Coma cluster by de Vaucouleurs & de Vaucouleurs (1970) and by Gunn & Melnick (1975) has suggested that the total light distribution differs little from the distribution of galactic light, and that the relative amount of light between galaxies is quite small. From a series of scans through the centre of the cluster de Vaucouleurs & de Vaucouleurs estimated that the total light of the central regions was about 40 per cent greater than that normally ascribed to the individual galaxies; they suggested that this extra light came from extensive haloes around the two central supergiants.

The limiting factor in any measurement of cluster surface brightness is the proper subtraction of the sky contribution which is much larger than the signal to be detected. Two kinds of variation of the sky brightness level need to be considered. Firstly there are slow variations caused by the motion of clouds and fog over nearby cities and by the change in pointing direction of the telescope; these variations can be removed by interpolating in time between successive measurements of the sky level. Secondly there are random short-term fluctuations caused by changes in the strength of auroral emission lines as a result of processes in the upper atmosphere; these variations occur on time scales of a few seconds and can only be eliminated by monitoring the sky continuously throughout the period of observation. To do this a separate telescope is necessary because the extended nature of the surface brightness distribution of the cluster precludes the use of chopping techniques (Gunn & Melnick 1975).

For the observations reported in this paper a 2-in. sky monitor was mounted on the optical axis of the 60-in. telescope on Mount Palomar. This small telescope was used to measure the brightness of a particular patch of sky whilst the main instrument carried out drift scans through the cluster at the sidereal rate. In this way a rectangular region of the cluster was mapped at two wavelengths with a resolution of 1.2 arcmin and a limiting sensitivity of about 1 per cent of the sky. Section 2 of this paper describes the equipment and the observing technique in detail, Section 3 describes the way the data were reduced, and Section 4 analyses the results. It appears that the total light of the cluster can be very little more than that due to the galaxies alone, and that the intergalactic background must have a very high mass-to-light ratio. If this background is made up of stars then more than 80 per cent of the cluster mass must be in stars less massive than $0.1\,M_\odot$.

2 The observations

The present observations were taken with the Palomar 60-in. telescope on three photometric nights in 1976 May using a two-channel photometer consisting of two ITT FW-130 S20 photomultipliers. In addition a 2-in *f*/5 refracting telescope was mounted on the optical axis of the main telescope in front of the secondary mirror. This sky monitor was fully orientable and could be accurately positioned by offsetting from the microswitches which limited its travel along each axis. The digitized pulse input into the stepping motors which governed this offsetting could also be used to drive the telescope at any desired rate in right ascension to compensate for the rotation of the Earth whilst the main telescope was carrying out drift scans. The two telescopes were aligned each night by centring both on Polaris using a 3-in finder attached to the sky monitor. This alignment was checked by scanning the small instrument through Arcturus while the star was centred in the main telescope. From this we estimate the pointing errors for the 2-in due to incorrect alignment and to flexure in its mount to be less than ten minutes of arc.

During the drift scans one channel only of the 60-in photometer was used to observe the cluster through a 30 arcsec by 70 arcsec rectangular aperture aligned with its longer edge lying north–south. The *g* and *r* bands of Thuan & Gunn's (1976) photometric system were used for all observations because of their avoidance of strong night sky lines and their relative insensitivity to changes in photomultiplier characteristics. The filters on the two telescopes were identical, and the photomultiplier tubes in the two photometers were maintained at dry ice temperature throughout the observing run. Discriminator curves for the photomultipliers drawn several times during the run failed to show any changes in instrumental characteristics, and measurements of the star BD +28 2169 taken before each scan did not reveal any detectable fluctuations in the sensitivity of the 60-in tube. The counts from the scan channel and from the sky monitor were integrated simultaneously by the 60-

in pulse-counting system during the scans and recorded every 5.35 s. Typical sky count rates in the red band were 500 000 counts per integration in the 2-in channel and 10 000 counts per integration in the 60-in channel.

A minimum of 14 standard stars were observed each night in order to determine extinction and instrumental coefficients. In addition the standard sequence of Huchra & Green (1975) in the neighbourhood of the variable galaxy X-Comae was reobserved in order to calibrate the iris photometry necessary to eliminate field star contamination of the scans. This sequence was supplemented by magnitudes for a few other stars in the field measured previously by one of us (JM) and by magnitudes transformed from the values of Huchra & Green for two fainter stars. The plate material used for iris photometry consisted of one green plate (103a-J + Wr 4) and one red plate (098-04 + RG1) taken with the Palomar 48-in Schmidt camera. These plate–filter combinations give a very close match to the photoelectric *g* and *r* bands (*cf.* Thuan & Gunn 1976).

Scans were carried out on the cluster through a maximum of 1.3 air-masses from −18 degree twilight until half an hour before moonrise each night. Before each scan a patch of sky 7 minutes of arc north of the 9-mag star BD + 27 2208 was centred in the 60-in aperture whilst the sky monitor was pointed so that its field of view (2.4 degrees in diameter) was centred well away from any bright star about 3 degrees south of the cluster centre. The surface brightness of the sky patch near BD + 27 2208 was used as the sky reference level for all surface photometry; this patch lies 2 degrees from the centre of the Coma cluster, is free of stars to the limit of the POSS prints and seemed sufficiently far from any bright star for scattered starlight to be negligible. With the telescopes in this configuration simultaneous sky measurements were carried out until about 100 000 counts had been accumulated in the 60-in channel. The main telescope was then moved to the star BD + 28 2169 which lies 40 minutes of arc west of the cluster centre and offset to the declination of the scan using the digital readout of the setting circle. At the same time the position of the 2-in. was adjusted to keep it pointing at the same area of the sky. After a star had been centred on the cross-hairs of the offset guider, the 60-in was moved about a minute of arc west, its tracking was switched off and simultaneously that of the sky monitor was switched on; the scan integrations in both channels were then started as the guide star passed through the cross-hairs of the offset guider. This complex procedure was employed to give the maximum possible accuracy in the starting position of each scan. We estimate that we know the position of each scan integration on the sky to within 5 arcsec in dec and 0.5 sec in RA. Each scan was stopped after 6 minutes at the right ascension of BD + 27 2208 and the telescopes were moved to measure the sky patch again. A complete scan cycle took about 11 minutes on average, so that the sky level in the main scan channel was measured directly with this frequency.

3 Data reduction

The raw data from the observing run consisted of 49 six-minute scans along 12 contiguous non-overlapping east–west strips through the Coma cluster. The central strip was scanned three times in each photometric band and all the other strips were scanned twice except for one which was scanned only once in the green. The first 66 five-second integrations along each scan were used in the final reductions so that the light from the observed area was divided into a 12 × 66 array of separate bins. The total region of the cluster covered in this way is a rectangle 14 arcmin wide and 78 arcmin long with its centre at

$$\alpha = 12^{\mathrm{h}}57^{\mathrm{m}}21^{\mathrm{s}};\ \delta = 28^\circ\ 10'16''(1950).$$

The counts received by the main telescope and by the sky monitor during each observation of the comparison sky patch were first averaged to get a mean sky ratio, $R(t) = \overline{C}_{60}/\overline{C}_2$, between the two telescopes. These ratios were found to drift by a few per cent at times when the sky brightness was changing substantially. Because of this we subtracted the large sky contribution from each scan integration using the interpolation formula,

$$C'_{60}(t) = C_{60}(t) - \left(R(t_1) + \frac{t - t_1}{t_2 - t_1}(R(t_2) - R(t_1))\right)C_2(t),$$

where t_1 and t_2 were the times of the sky observations before and after each scan. The maximum systematic error of any part of one scan due to incorrect sky subtraction was estimated from repeated scans to be about one per cent of the sky. This figure is confirmed by the more detailed analysis of Section 4.2 and shows that our observing technique has reduced the level of the noise caused by sky fluctuations to that of the Poisson noise in each integration arising from count statistics; it is more serious, however, because the errors in adjacent bins are not independent. We note at this point that the contribution of stars to the sky counts received by the 2-in telescope is small but not negligible. Using the numbers given by Allen (1972) for the integrated brightness of stars fainter than fourth magnitude near the Galactic pole, we find that such stars are responsible for about 15 per cent of the counts recorded by the sky monitor. This star contribution introduces *no* systematic errors into our sky correction procedure, but causes a slight increase in the noise. It is probably the main cause of the drift in the count ratio described above, since the magnitude of the drift is consistent with a 15 per cent fixed component in the 2-in counts.

Instrumental and extinction coefficients derived from the observations of system standards were used to convert the individual sky-subtracted scans to a standard system before averaging repeated scans. Since we observed standards to within one magnitude of the total brightness of the sky in our scanning aperture, we can neglect any possible non-linearities in the photometric system (*cf.* Sandage 1975). The averaging of repeated scans reduced the systematic sky-subtraction errors as well as the random noise, since the errors in different scans are independent; it also introduced a slight smoothing of the data because of small errors in the starting position of each scan. In the resulting mean scans any star brighter than 18-mag is clearly visible above the noise. In addition the scattered light from a bright star contributes substantially to nearby bins even when the star itself is outside them. In particular a correction must be made for the scattered light of the 7-mag star BD + 28 2171 over much of the central region of the cluster. In order to estimate the necessary corrections for scattered starlight a number of drift scans were made in both colours near the 2-mag star ϵ Boo. It was found that within 30 arcmin of the star the amount of scattered starlight in any bin could be represented with sufficient accuracy as a function only of the brightness of the star and of its distance from the bin centre, and further that in each photometric band this function was well approximated by two power laws, one of slope ~ 3 within about 6 arcmin of the star and one of slope ~ 1.5 beyond this distance. Similar star profiles were determined photographically by Kormendy (1973); it should be emphasized, however, that such profiles depend quite strongly both on the wavelength of the light observed and on the telescope and auxiliary equipment used.

During the observing run the two stars brighter than 11 mag near the observed region of the cluster were measured several times on the $g-r$ photometric system. The photoelectric sequence described in Section 2 extends to 18.0 in g and 17.5 in r and was used to calibrate iris photometry of all objects in the observed area which appeared stellar on an extremely deep IIIa-J plate of the field taken by J. E. Gunn with the Palomar 48-in Schmidt (this is the plate reproduced in Fig. 3). One plate in each photometric band was measured, and the readings of the $X-Y$ base on the photometer were used to derive positions for each star. Comparison of the positions found separately in this way from the two plates showed that they were accurate to about 2 arcsec, and also that there were no misidentifications. The standard deviation in magnitude of the standard stars from the cubic calibration curve fitted to the iris readings was about 0.07 in each band, but a rather more conservative estimate of 0.1 mag for the random errors is probably more appropriate. Inspection of the fitted curves showed that the brightness of stars near and beyond the calibration limit was systematically overestimated. This was partially corrected by arbitarily setting $g = 18.5$ for all stars fainter than $g = 18.0$ and $r = 18.1$ for all stars fainter than $r = 17.6$. The errors introduced by this procedure have negligible effect on the results discussed below.

The scattered light from the two brightest stars near the observed area was subtracted from the mean scans using the measured star profiles. The positions and magnitudes of the other stars were then used in conjunction with the scattered light profiles to simulate the stellar light contribution to the observed arrays. Two such simulated arrays were constructed for each photometric band. One contained the best estimates of the stellar contribution to each bin, and was used to correct the observed arrays wherever star contamination was not too serious. The other contained the maximum possible stellar contribution to each bin derived under the assumption of a maximum possible position error for each star of 10 arcsec in dec and 1 second in RA, together with a possible systematic error of 0.1 in the magnitudes of stars fainter than the limit of the photoelectric sequence established in the present run (16.5 mag at both wavelengths). This latter array was used to decide which bins might be too badly contaminated by stars and should be rejected. The appropriate rejection criterion depends to some extent on the way the data are to be used; the criteria adopted will be described in detail as they appear in further analysis.

To avoid mixing independent observational data from the two photometric bands, and in the general interests of clarity, much of the analysis of Section 4 will be carried out in terms of the mean observed counts in each bin. These counts can be converted to standard g and r surface brightnesses in mag/sq. arcsec using the following equations,

$$\mu_g = 32.03 - 2.34 \log_{10} C_g - 0.16 \log_{10} C_r$$
$$\mu_r = 31.59 - 2.77 \log_{10} C_r + 0.27 \log_{10} C_g. \tag{1}$$

4 Results

4.1 OVERALL LIGHT DISTRIBUTION

Fig. 1 presents a comparison of data from the present investigation with the smoothed averaged scans of de Vaucouleurs & de Vaucouleurs (1970, Fig. 7). De Vaucouleurs & de Vaucouleurs observed with a blue-sensitive photocathode and no filter; their results have been scaled to the r band using their estimate of the equivalent B brightness and the mean $B - r$ colour of 1.2 which is appropriate to elliptical galaxies. The effective east–west resolution of their smoothed data is similar to that of the present observations, but the north–south width of their strip is half that of our aperture. In addition their scan is displaced 22 arcsec northwards from the scan with which it is compared. Agreement between the two sets of data can be seen from Fig. 1 to be quite good. (Our g-band data would give a very similar picture). However, our observing method eliminates most of the noise caused by fluctuations in sky brightness, and as a result both the theoretical and the achieved sensitivity of the present observations are better than those of the earlier investigation. Further, the much larger region of the cluster we surveyed allows safer and more detailed interpretation than did the results of de Vaucouleurs & de Vaucouleurs.

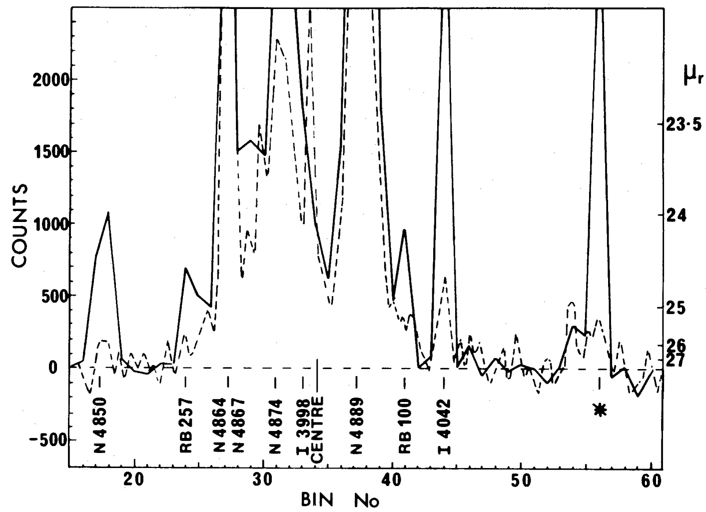

Figure 1. Comparison of data from the present investigation with the data of de Vaucouleurs & de Vaucouleurs (1970). The solid line is the mean of two sky-subtracted scans in the r band at dec +28° 14.3′ (1950). The vertical scales give the number of counts per integration and the equivalent mean surface brightness, μ_r, in mag/sq. arcsec. The horizontal scale gives the position of each integration in the scan (1 unit = 5.35 sec in RA). The dashed line is the mean of de Vaucouleurs' ten scans at dec +28° 14.7′ with the sky contribution removed by linear interpolation between its apparent values at each end. These data have been scaled as explained in the text. The positions of some contributing galaxies and of a field star are indicated.

Contour maps of the light distribution in the observed region of Coma are presented in Fig. 2. These were constructed in the following manner. The estimated maximum possible stellar contribution to each bin was compared with the observed light in that bin. If this contribution was either less than 100 counts or was less than half of the observed light, the observed counts were corrected for stellar contamination using the 'best guess' values for the star contribution; otherwise the data for the bin were rejected. This rejection procedure is statistically biassed but was employed in order to retain the maximum amount of accurate information (about 30 per cent of the bins had to be rejected). The remaining data were smoothed by convolution with a Gaussian of 3.5 arcmin full width at half maximum and contours were drawn for the resulting array.

It is immediately evident from Fig. 2 that the light distributions at the two wavelengths are very similar even at the lowest meaningful contour levels. We note here, however, that as a result of the substantial fraction of the data which was rejected in order to eliminate stellar contamination, the contour maps of Fig. 2 are not suitable for quantitative analysis. The contours are 'swollen' somewhat by the smoothing process and are slightly affected by the biassed star correction procedure. Contour maps drawn with different smoothing beamwidths and different criteria did not differ substantially from Fig. 2, which can be considered to give a good qualitative representation of the total distribution relative to the zero-point defined by the comparison sky patch. The similarity of the distributions in the two photometric bands is strong confirmation of the accuracy of the underlying photometry since they are derived from entirely disjoint sets of observations. Fig. 3, which superposes the red contours of Fig. 2 on a photograph of the observed region, shows clearly that the light distribution in the cluster follows the galaxy distribution very closely. The two supergiant galaxies in the cluster centre can be seen to have the common envelope noted by de Vaucouleurs & de Vaucouleurs (1970); the surface brightness between them does not drop much below 25 mag/sq. arcsec in the green. (This can be seen in the unsmoothed data and is *not* an effect of the smoothing.) There is no clear colour gradient with radius in this envelope. A particu-

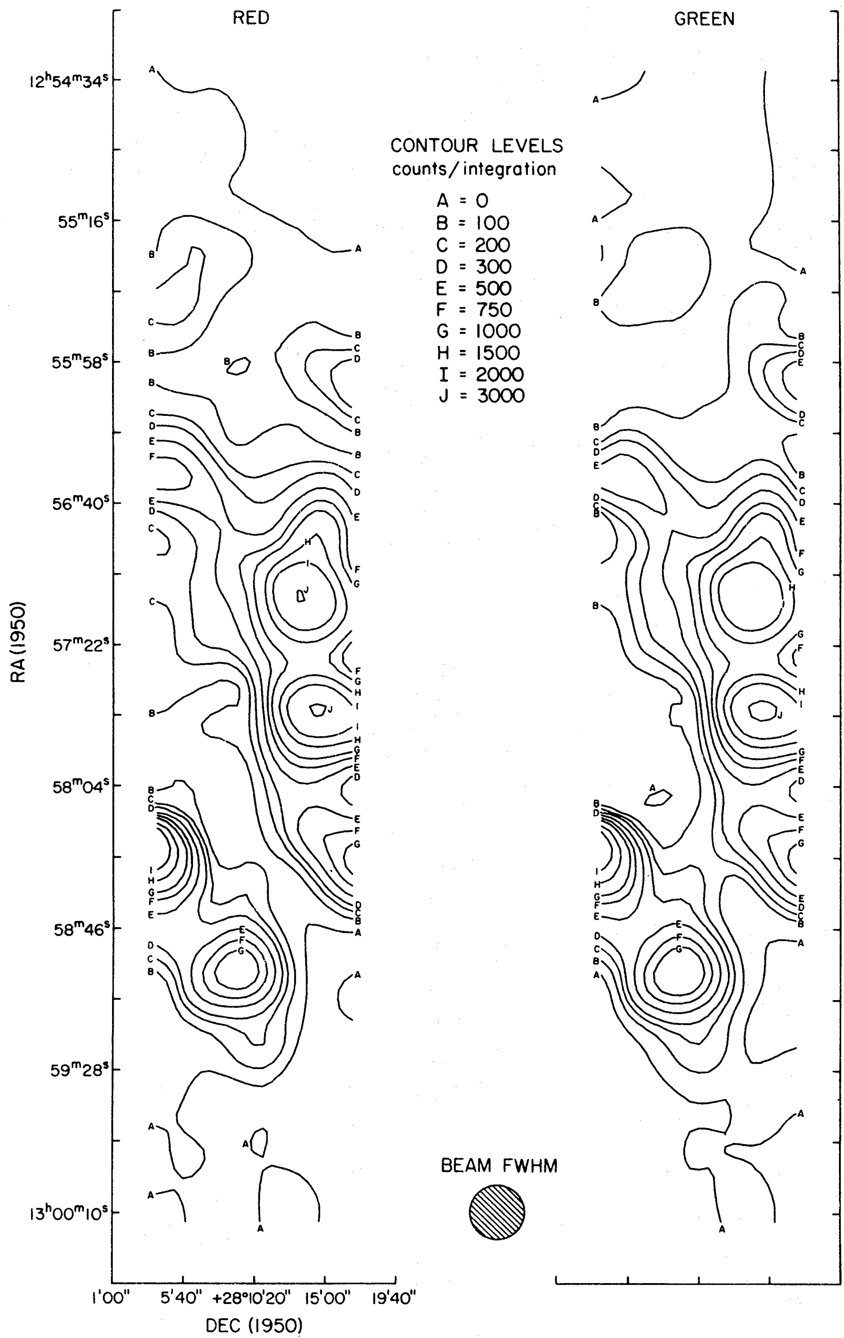

Figure 2. Contour maps of the surface brightness of the observed region in the g and in the r wavebands. After removal of night-sky and foreground star contamination the data were smoothed with a Gaussian of the illustrated half-power beam size. The contour units are mean counts per integration and the contour levels are as indicated. 100 count/integ. is equivalent to a surface brightness of 27.0 mag/sq. arcsec in g and 26.6 mag/sq. arcsec in r.

larly noticeable feature is the ridge of luminosity extending south–west from NGC 4874 which is associated with an apparent subcluster of galaxies. This structure was previously noticed by Welch & Sastry (1971) and by Kormendy & Bahcall (1974) on isodensitometer tracings of the central part of the cluster; it can be seen from Fig. 2 to be rather redder than the central regions. In contrast the large spiral galaxy NGC 4921 which lies 21 arcmin east of the centre is clearly bluer than the cluster core. It is striking that the surface brightness has already dropped below the limit of detectability 7 arcmin south of the elliptical NGC

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4889 which is the brightest galaxy in the whole cluster. This distance corresponds to only 270 kpc (we take $H_0 = 50$ km/(s Mpc) here and in all that follows) and so any halo surrounding the supergiant or any all pervasive intracluster medium must be of quite low luminosity.

4.2 ERROR ANALYSIS

The negative count regions seen at the end of the observed strip in Fig. 2 suggest that the surface brightness of the comparison patch may actually be *greater* than the mean intergalactic brightness outside the cluster centre. We now check whether a zero-point correction is required and analyse the sources of error in our data. For the quantitative analysis which forms the rest of this paper we correct the mean sky-subtracted scans for stellar contamination in an unbiased way by rejecting all bins for which the estimated maximum possible stellar contribution is more than 500 counts, and then correcting the rest using our 'best guess' values for the starlight. Employing this criterion results in 16 per cent of the bins being rejected and the others being corrected by an average of 32 counts per bin. Since the *systematic* error in the stellar correction is certainly less than 25 per cent, we may conservatively estimate that our star subtraction procedure introduces an overall zero-point error into the corrected scans with a dispersion, σ_*, of 8 counts per bin.

To evaluate the other sources of error in the scans we anticipate somewhat the results of the following section. We there eliminate from the scans all light from galaxies brighter than $V_{25} = 18.0$ and analyse the remaining data. We find little intergalactic light in the cluster core, and no detectable intergalactic light further than about 24 arcmin from the centre. As a result we may use the observed counts in intergalactic regions far from the cluster core to analyse the errors in our data. In Table 1 we present some statistics of the distribution of counts in all the intergalactic bins further than 30 arcmin from our adopted cluster centre (halfway between NGC 4889 and NGC 4874). In this table N is the number of bins which lie in the required region and are contaminated by neither stellar nor galactic light, $\bar{C}$ is the mean of the counts in these bins, and s_t is the estimated standard deviation of the counts about the true mean. To evaluate the contribution of sky subtraction errors to the overall dispersion we have separated each set of data into 24 groups containing bins at the same end of the same mean scan, and for each group we have calculated a local mean and an estimate of the variance about the true local mean. In Table 1 s_a is the estimated standard deviation of the local means about the true overall mean, and s_l is the square root of the number-weighted mean local variance. Under the hypothesis that the errors in each bin arise from a random noise component of dispersion σ_1 superposed on a systematic local sky subtraction error of dispersion σ_2, the following relations should approximately hold

$$\sigma_1 = s_l; \quad \sigma_2{}^2 = s_t{}^2 - s_l{}^2; \quad \sigma_2{}^2 = s_a{}^2 - 24\, s_l{}^2/N.$$

The fact that σ_1 and σ_2 can be found so that all three of these relations are well satisfied shows that this model describes the error distribution adequately.

For the quantitative analysis of the following section we correct our data to the zero-point defined by the intergalactic level of the outer parts of the cluster using the values of

Table 1. Error statistics.

	N	$\bar{C}$	s_t	s_a	s_l	σ_1	σ_2	σ_*	$\Delta\bar{C}$
Green	136	−20	90	61	73	73	53	8	18
Red	134	−35	93	59	82	82	46	8	17

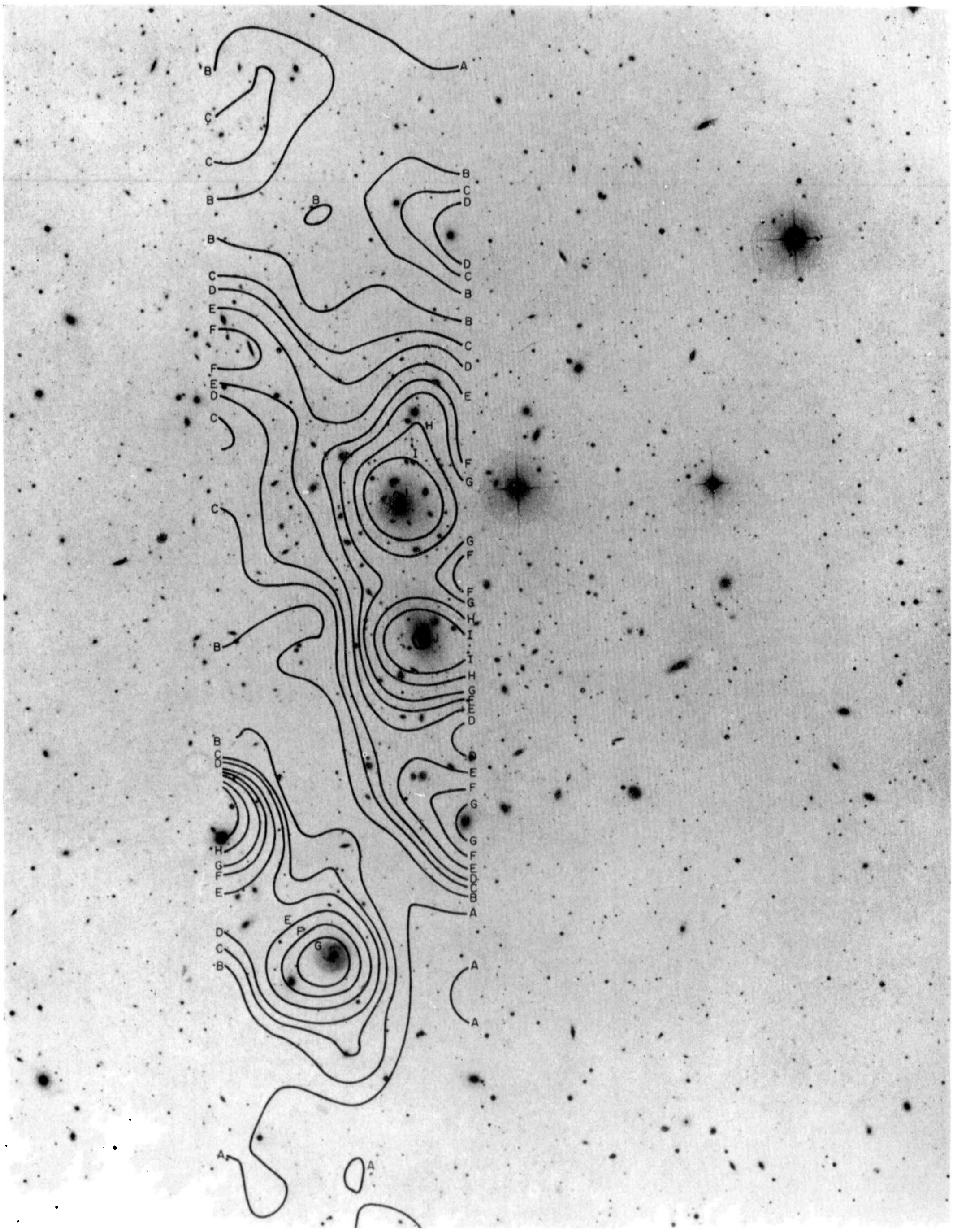

Figure 3. Superposition of the *r* contours of Fig. 2 on a photograph of the central part of the Coma cluster. North is to the right and east is downwards.

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$\bar{C}$ in Table 1.* It appears that our comparison patch was brighter than the mean blank sky at the ends of the scans by about 28 mag/sq. arcsec; this excess was most probably scattered starlight in a diffraction spike of BD+27 2208. When calculating uncertainties in the numbers given below we shall use the values of σ_1, σ_2 and σ_* given in Table 1. Note that any fluctuations in true surface brightness due, for example, to faint stars or galaxies will have caused us to overestimate σ_1; since the noise due to count statistics alone is expected to have a dispersion of 70 counts per bin, other sources of random noise cannot be very important. The low values found here for σ_2 confirm the statement in Section 3 that our sky-subtraction technique has reduced the effects of sky brightness fluctuations to an rms value of less than one per cent of the sky in individual scans. When evaluating errors below we shall always make the conservative and unrealistic assumption that sky-subtraction uncertainties cause the overall zero-point of each scan to be uncertain by an amount σ_2. With this assumption we can estimate the overall rms uncertainties in the zero-points of our data resulting from random noise, sky-subtraction errors and inaccurate corrections for stellar contamination; these uncertainties are listed as $\Delta\bar{C}$ in Table 1.

4.3 TOTAL AND INTERGALACTIC LIGHT

We now analyse our mean sky and star corrected scans in much greater detail in order to obtain quantitative measures of the total luminosity and of the amount of intergalactic luminosity which may be present. We divide our bins into seven groups according to the distance of their centres from a point midway between the two supergiant galaxies in the cluster core. In the first column of Table 2 we give the outer radius in arcmin of each group, and in the second the total number of bins it contains. All of our bins lie within 42 arcmin of the adopted centre. N_t in Table 2 is the number of bins in each group which survive the starlight subtraction procedure in both wavebands, R_* and G_* are the average stellar corrections applied, and the mean corrected counts in the remaining bins are listed as R_t and G_t along with the rms dispersions about these means. (The values of $\bar{C}$ listed in Table 1 have been used to correct all the data in Tables 2 and 3 to the zero-point defined by the blank sky near the end of the scans). Comparison of N_0 and N_t in Table 2 shows that a somewhat greater fraction of bins were rejected in the inner part of the scans than in the outer part. The effect is significant but not large, and is presumably caused by the misidentification of a few faint compact galaxies as stars. The starlight corrections show little sign of a strong trend with radius.

For each group of bins we can compute total magnitudes using the values of N_0, R and G_t in Table 2 and equations (1); further we can calculate the standard error in these magnitudes from the quoted dispersions in R_t and G_t and the values of σ_1, σ_2 and $\Delta\bar{C}$ given in Table 1. The g and r magnitudes found for each group in this way are listed along with their

Table 2. Luminosity distribution in counts/integration.

R	N_0	N_t	N_b	R_*	R_t	R_b	G_*	G_t	G_b
6	66	52	5	44	1340 ± 1878	160 ± 222	46	1364 ± 1908	195 ± 114
12	142	114	31	29	334 ± 429	139 ± 138	32	283 ± 411	93 ± 148
18	136	105	46	30	263 ± 706	51 ± 103	31	245 ± 646	50 ± 101
24	127	109	35	34	250 ± 643	34 ± 90	36	231 ± 650	18 ± 104
30	125	106	59	25	89 ± 239	0 ± 95	31	61 ± 241	−19 ± 83
36	126	112	78	22	26 ± 134	−11 ± 88	25	15 ± 124	−6 ± 81
42	70	62	55	15	39 ± 142	17 ± 97	16	36 ± 143	11 ± 97

*We thank a referee for stressing the importance of this correction. As a result of it the numbers appearing below differ somewhat from those given in a preprint version of the paper.

Table 3. Luminosity distribution in magnitudes

R	g	r	V	V_{25}
0–6	10.38 ± 0.09	9.97 ± 0.09	10.20	10.54
6–12	11.24 ± 0.09	10.62 ± 0.08	10.98	11.09
12–18	11.45 ± 0.15	10.94 ± 0.14	11.23	11.37
18–24	11.59 ± 0.13	11.07 ± 0.12	11.37	11.36
24–30	13.04 ± 0.32	12.17 ± 0.22	12.69	12.27
30–36	14.53 ± 0.90	13.46 ± 0.58	14.11	13.52
36–42	14.23 ± 0.49	13.74 ± 0.45	14.03	14.51
0–24	9.55 ± 0.07	9.05 ± 0.07	9.34	9.53
0–42	9.48 ± 0.09	8;97 ± 0.08	9.26	9.41

standard errors in Table 3; the large errors on the magnitudes of the outer two groups are caused by zero-point uncertainties and are unreliable. Remembering that the zero-point error, $\Delta\bar{C}$ is constant from group to group, but that other errors are independent, we can similarly calculate magnitudes for the whole observed region, and for that part of it within 24 arcmin of the centre which contains almost all the observed light. These magnitudes and their standard errors are also given in Table 3. Our most accurate magnitudes are seen to be those for the total light in our strip within 24 arcmin of the centre; these have errors of only 0.07 mag in each waveband.

A transformation between the Thuan & Gunn and the *UBV* photometric systems has been derived by one of us (JM) using 17 late-type standard stars. The resulting equations,

$$V-g=0.14-0.37(B-V)\ ;\ g-r=-0.47+1.01(B-V), \tag{2}$$

can be used to get V magnitudes for our data of comparable accuracy to our g and r magnitudes, but the $(B-V)$ colours derived from them will be systematically too red because of the different spectral ranges measured by the $(B-V)$ and $(g-r)$ indices and the subsequent inapplicability of the transformation to galactic light. For this reason we give the values of V found for our data in Table 3, but refrain from calculating $(B-V)$ values. J. Godwin has kindly supplied us with positions, V_{25} magnitudes and mean surface brightness for almost all the galaxies in our observed region. (These will be published in *Monthly Notices* as Godwin & Peach 1977). Summing these data in the various radial ranges gives the numbers listed as V_{25} in Table 3. Clearly only a small fraction of the cluster luminosity comes from outside the V_{25} isophotes of the galaxies; a comparison of the V and V_{25} magnitudes given in Table 3 suggests that between 15 and 20 per cent of the visual light of the cluster comes from galactic haloes, faint galaxies and the intergalactic medium. (The anomalously low value of V in the 24–30 arcmin group results from the rejection of the light of a bright galaxy (V_{25} = 13.68) on which a bright star is superimposed.) Unfortunately the uncertainty in this number is hard to estimate because of its sensitivity to the relationships between the various photometric systems employed. We return to the question of intergalactic luminosity later in this section.

A mass-to-*total*-light ratio for the region observed can be found using the numerical model of White (1976b) for the Coma cluster. The mass of the projected model in the corresponding region is 190 ± 29 model units where this mean and rms deviation have been calculated from 12 different projections at each of the five times averaged to get White's mean model. This implies an actual mass of $6.4 \pm 1.3 \times 10^{14} M_\odot$ where the quoted error includes a contribution from the uncertainty in the model mass unit. With the g magnitude found above this gives rise to a mass-to-light ratio $(M/L)_g = 233 \pm 53$ in solar units, whilst using the derived V magnitude we get $(M/L)_V = 207 \pm 47$. The errors now also include an uncertainty of 0.10 in the magnitudes and should be a good measure of the overall uncertainty in the mass-to-light ratio of the cluster. When fitting the same numerical model to the distribution of *galactic* light determined by Oemler (1974) for the cluster as a whole, White (1976b) found a visual mass-to-light ratio of 258 ± 36. Again it is evident that very little excess light is present in the cluster outside of the galaxies.

We now turn specifically to the problem of intergalactic luminosity, and use data from the present investigation alone to put direct limits on the contribution of any intracluster medium to the total cluster light. To do this we exclude galactic light from our scans by throwing out all bins whose outer edge lies within a projected distance 1.5 R of a galaxy brighter than V_{25} =18.0, where R is an equivalent radius of the galaxy's V_{25} isophote derived from its magnitude and mean surface brightness. The number of bins left in each radial range after this process is given as N_b in Table 2; in the innermost region only five of the 66 bins are definitely uncontaminated by light from within the V_{25} isophotes of galaxies! Luckily the situation is much better in the other groups. The mean counts in these 'intergalactic' bins are given as R_b and G_b in Table 2 together with the corresponding rms dispersions. These counts contain contributions from the outermost parts of galaxies and from galaxies fainter than 18 mag as well as from any true intergalactic medium which may be present, and, in particular the two inner groups are affected by the common halo around the two central supergiants. It is clear that no intergalactic light is visible above the noise beyond about 20 arcmin from the cluster centre. This was the justification for our using these data in the last section to set the sky level and to analyse the noise in our observations, and may be quantified as follows. Within 42 arcmin of the cluster centre Godwin's photometry agrees with that of Oemler (1974) in giving a radial dependence of the integrated surface brightness of *galactic* light, $S \propto r^{-1.75}$. Assuming a model of the form $S = ar^{-1.75} + b$ for the background data in the outer six groups of Table 2, we can use a χ^2 test to put limits on the parameter a. The results allow us to say that our data is inconsistent at the one per cent level with *all* models in which the radially varying component of the background contributes an average of more than 24 count/integ. in r or 20 count/integ. in g to the bins used to define the background level. These numbers are not much larger than the *one sigma* zero-point errors that we have adopted.

We can get an estimate of the ratio of the total light of any intergalactic background to that of the cluster as a whole by assuming that the mean background values in Table 2 are representative of the radial ranges for which they were derived. This is probably a good assumption since the mean radius of the bins contributing to R_b and G_b is in all cases close to that of the group as a whole, and in addition the intergalactic medium should, by hypothesis, be smoothly distributed. Such estimates can be calculated from Table 2 using N_0, N_t and N_b, and either R_t and R_b, or G_t and G_b; their standard error can be found from the dispersions quoted in Table 2 and the values of σ_1, σ_2 and $\Delta\bar{C}$ given in Table 1. For our data as a whole we find values for L_b/L_t of 0.19 ± 0.07 in r, and 0.16 ± 0.08 in g. Much of the noise in these estimates comes from the ends of the scans where little galactic light is seen. Restricting ourselves to the region within 24 arcmin of the centre we obtain 0.20 ± 0.06 in r, and 0.18 ± 0.05 in g. Since the errors in the two wavebands are almost entirely independent we propose 0.19 ± 0.04 as a reasonable estimate of the ratio of background to total luminosity. We stress again that this estimate is effectively an upper limit to the luminosity of any truly intergalactic background since most of the 'intergalactic' light may come from material which is bound to individual galaxies. Hence 25 per cent would seem to be a conservative upper limit on the amount of cluster light which might come from a true intergalactic background. The small amount of light that we see outside of the individual galaxies is in general agreement with the photoelectric results of de Vaucouleurs & de Vaucouleurs (1970) and Gunn & Melnick (1975) for the Coma cluster, and with those of Baum (1973) for two other clusters.

Combining our limit on the luminosity of any intergalactic background with the result of White (1977) that at least 80 per cent of the cluster mass must be present in such a background, we obtain a lower limit of 700 on the visual mass-to-light ratio of the material which binds the cluster. This result was anticipated by de Vaucouleurs & de Vaucouleurs (1970) but the present data establish it much more strongly than did their scans of a single strip through the cluster. If the background is made up of stars which were stripped from the outer parts of galaxies at an early stage of cluster evolution, then 80 per cent of the mass of the cluster consists of stars less massive than 0.1 $M_\odot$.

Conclusions

The photometry reported in this paper leads to the following conclusions:

(i) The light distribution in the Coma cluster follows the galaxy distribution closely. There is a common envelope surrounding the two central supergiant galaxies and a bridge of luminosity extends from the centre towards the south-west.

(ii) The total luminosity of the cluster is very close to that found by summing the luminosities of the individual galaxies. In conjunction with an N-body cluster model the present data give a total visual mass-to-light ratio of 207 ± 47 for the cluster.

(iii) The intergalactic medium which appears to be necessary to bind the cluster cannot contribute more than 25 per cent of the cluster light. It must therefore have a visual mass-to-light ratio of at least 700.

Acknowledgments

We wish to thank all the people who helped us to develop and to operate the 2-in system; in particular, Larry Blakee, Earle Emery, Jerry Fridenberg and Bill McLellan in Pasadena, and Safari Glenn and Bud Smith on the mountain. Chip Williams skillfully drove the telescope throughout the complicated observing programme. We also thank Dr James Gunn for support and advice during the early stages of this project and Dr David Rogstadt for supplying us with smoothing and contour plotting routines.

SDMW thanks the Hale Observatories and the Astronomy Department of the California Institute of Technology for their hospitality during a visit which was made possible by an SRC travel grant. JM was supported throughout this work by an AURA Fellowship.

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