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PHOTOGRAPHIC MEASUREMENTS OF THE DIFFUSE LIGHT IN THE COMA CLUSTER

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The diffuse background light in the Coma cluster is measured using isodensity tracings of *B*, *G*, *V*, and *R* photographic plates taken with the Palomar 1.2-m Schmidt telescope. The isodensity contours are calibrated using the star profile derived by Kormendy (1973). Between 4 and 14 arc min from the center, the surface brightness of the diffuse light decreases from $\sim$ 26 to $\sim$ 28 *G* magnitudes arc sec^{-2}. The total magnitude in this annulus is G = 11.22, which is $\sim$ 45% of the light in galaxies alone, or $\sim$ 30% of the total. This does little to alleviate the "missing mass" problem. The isodensity contours and the equivalent profile of the diffuse light closely parallel the distribution of light in galaxies, implying no strong mass segregation. However, the background light appears to be bluer than the galaxies. This is consistent with the hypothesis that the background consists of stars tidally stripped from galaxies, which generally become bluer at larger radii. The present technique is very different from methods used in the past. Comparison of a variety of measurements shows that a reasonably consistent body of data on the background light now exists.

Key words: clusters of galaxies—intergalactic matter

I. Introduction

The "missing mass" problem in clusters of galaxies has stimulated numerous efforts to search for matter outside of the visible galaxies (see Tarter and Silk (1974) for a review). In particular, searches in the Coma cluster for a diffuse luminous background have been undertaken by Zwicky (1951), de Vaucouleurs (1960), Gunn (1969), de Vaucouleurs and de Vaucouleurs (1970), Welch and Sastry (1971, 1972), Kormendy and Bahcall (1974, hereafter KB), Gunn and Melnick (1975), Melnick, White, and Hoessel (1977, hereafter MWH), and Mattila (1977). The photoelectric searches have been the most quantitative. However, they suffer from the problem that only one picture element is measured at a time. Then (a) the detection limit is relatively high because of the short integration time; (b) the area covered is relatively small; and (c) the all-important sky subtraction problem is particularly severe, because of (a) and (b), and because the sky brightness varies greatly on time scales short compared to the time taken to move the telescope from object to sky. A reasonably satisfying attempt to solve these problems has been made by MWH, who used another telescope to monitor the sky during the observations. However, photographic plates have the advantage of being essentially immune to the above problems. Instead, they suffer from severe (in the present context) spatial sensitivity variations. Despite this, the currently best technique for measuring a cluster background is probably photographic. Many plates of the same cluster are taken and all but the most uniform ones are discarded. Then background variations are modeled and corrected for by using two-dimensional digital maps of the remaining plates. Such techniques have been described by Jones et al. (1967), but are difficult, and have not been applied to the present problem. Even carried to extremes, neither photograpic nor photoelectric methods are wholly reliable on scales of 0°.5–1°. Confidence in the results will probably require the agreement of many studies of both kinds, using a variety of detectors and measuring engines.

With this in mind, we report here a photographic measurement using calibrated isodensity tracings. This technique is radically different from photoelectric photometry, and the calibration and zero-point derivation from star profiles are different from standard photograpic photometry. The method is also simple enough that many plates can be processed quickly. The light distribution can therefore be measured over a larger area than was studied previously.

In section II we describe the observations and reductions. The results are discussed in section III, and section IV summarizes the conclusions.

II. Observations and Reductions

The photographic plates were obtained with the Palomar 48-inch (1.2-m) Schmidt telescope. In this telescope an important source of vignetting is produced by the four vanes which hold the plateholder. At an angle θ (in degrees) from the optical axis, these cover a fraction 0.0037θ of the aperture in the four directions at 45° to the vanes, and $1/\sqrt{2}$ times as much in the four directions parallel to the vanes. We have eliminated this effect by covering the front of the vanes with two-inch wide tape. They are then hidden behind the tape out to a radius of 6°. The field is therefore uniform over the 5°.7 *diameter* outside of which the vignetting produced by the 72-inch (1.8-m) mirror begins.

The bandpasses used were B (3, 103a-O + GG 13 plates exposed ~ 10 min each), G (3, 124-01 or IIIa-J + Wr4 plates exposed ~ 40 min or 2.25 hrs), V (6, 103a-D + Wr12 plates exposed ~ 30 min), and R (1, 098-04 + RG1 plate exposed 35 min).

All plates were measured with the Photometric Data Systems microdensitometer in the Berkeley Astronomy Department of the University of California. Approximately square areas 1°–2°.5 in width and centered on the two supergiant galaxies were scanned with a rectangular aperture, usually 50 × 200 μm (3 × 13 arc sec). A series of isodensity tracings (IDT) were then produced from each scan, with different zero points. That is, the fraction of a density step above sky at which the first symbol change occurs was progressively changed. Figure 1 shows one of the most sensitive IDTs, which reaches slightly fainter than the one in KB. In several cases the data were smoothed to improve the sensitivity, by making running averages of 3 to 6 consecutive points horizontally and the same number of scan lines vertically. Smooth contours were then hand drawn on the tracings, as delineated by the symbol changes. A collection of contours is shown in Figure 2. We will express the cluster profile in terms of the equivalent radius $r \equiv (A/\pi)^{1/2}$ of each contour. Here A is the area enclosed by a contour, as measured with a planimeter. The adopted center is the point midway between NGC 4874 and NGC 4889, as in Rood et al. (1972).

North of the cluster center the measurements are dominated by light from the seventh magnitude star BD +28°2171. We therefore used the contours south of the line joining NGC 4874 and NGC 4889, and multiplied the area by two. However, the cluster is not quite symmetrical about this line (see Fig. 1); there is an extension to the southwest, and another slightly north of east. The northeast extension is omitted from the above measurement. To test the sensitivity of the results to this asymmetry, we have also measured the area south of a line passing through the cluster center at a position angle of 64°. This is essentially the major axis of the cluster (Rood et al. 1972). The area used then includes both of the above features. The two resulting radii were always nearly equal, and the mean was adopted.

The surface brightness detected by an isodensity contour was calibrated using the star image profile produced by the Schmidt telescope (Kormendy 1973). The technique is described in KB and Kormendy (1973). Essentially, we measured the radius of a contour around a star, and obtained the corresponding brightness from the star profile. Usually two or three stars were used, avoiding any regions of the plate where the background was nonuniform. The calibrations from different stars typically agreed to ~ 0.05 G magnitude arc sec^{-2} (hereafter μ) and a mean was adopted. Various optical effects that might produce spurious galaxy halos have been examined in KB, and were shown to be negligible.

Magnitudes of the standard stars are given in Table I. G is obtained from B and V using the transformation $(B-G) = 0.65\ (B-V)$ derived in KB (see also Thuan and Gunn 1976). A similar transformation was derived for R using r magnitudes for 18 Hyades and Pleiades stars in the range $0.1 \leqslant (B-V) \leqslant 1.55$ (Thuan and Gunn 1976). A plot of $(V-r)$ *versus* $(B-V)$ gave: $(V-r) = -0.40 + 0.70\ (B-V)$, with a rms scatter of ~ 0^m.02. Normalizing, as usual, to zero color for an A0 V star gives $(V-R) = 0.70\ (B-V)$ as the definition of our R magnitudes.

III. Results and Discussion

The G profile of the background light is shown in Figures 3(a) and (b). In (a), the different colors have been converted to G with the above transformations and an assumed color for the diffuse light of $(B-V) =$ 1^m.03. This is the mean color of the two supergiant galaxies (de Vaucouleurs, de Vaucouleurs, and Corwin 1976). The B points are high, suggesting that the real color is much bluer than the one assumed. The other points define the profile fairly well, with a scatter of 0.3–0.4 μ. To better define both the color and shape of the profile, Figure 3(b) shows the different color measurements vertically shifted together to minimize the scatter. The profile is normalized to G because this set of measurements is closest to the B system in which the star profile was determined (there are too few B points for an accurate zero point). The vertical shifts between bandpasses give colors, which are converted

TABLE I

CALIBRATION STARS

Name	α(1950)	δ(1950)	B*	G	V*	R
BD +28°2171	12^{h}57^{m}08^s	+28°20'07"	7.61	7.34	7.19	6.90
BD +28°2350	12 57 09	28 30 30	8.60	8.32	8.16	7.85
BD +29°2348	12 56 10	28 35 21	7.20	7.05	6.97	6.81
BD +28°2170	12 56 16	27 44 43	8.62	8.20	7.97	7.51
BD +28°2167	12 52 42	28 02 17	8.50	8.07	7.84	7.38

* B and V magnitudes are taken from Blanco et al. (1968).

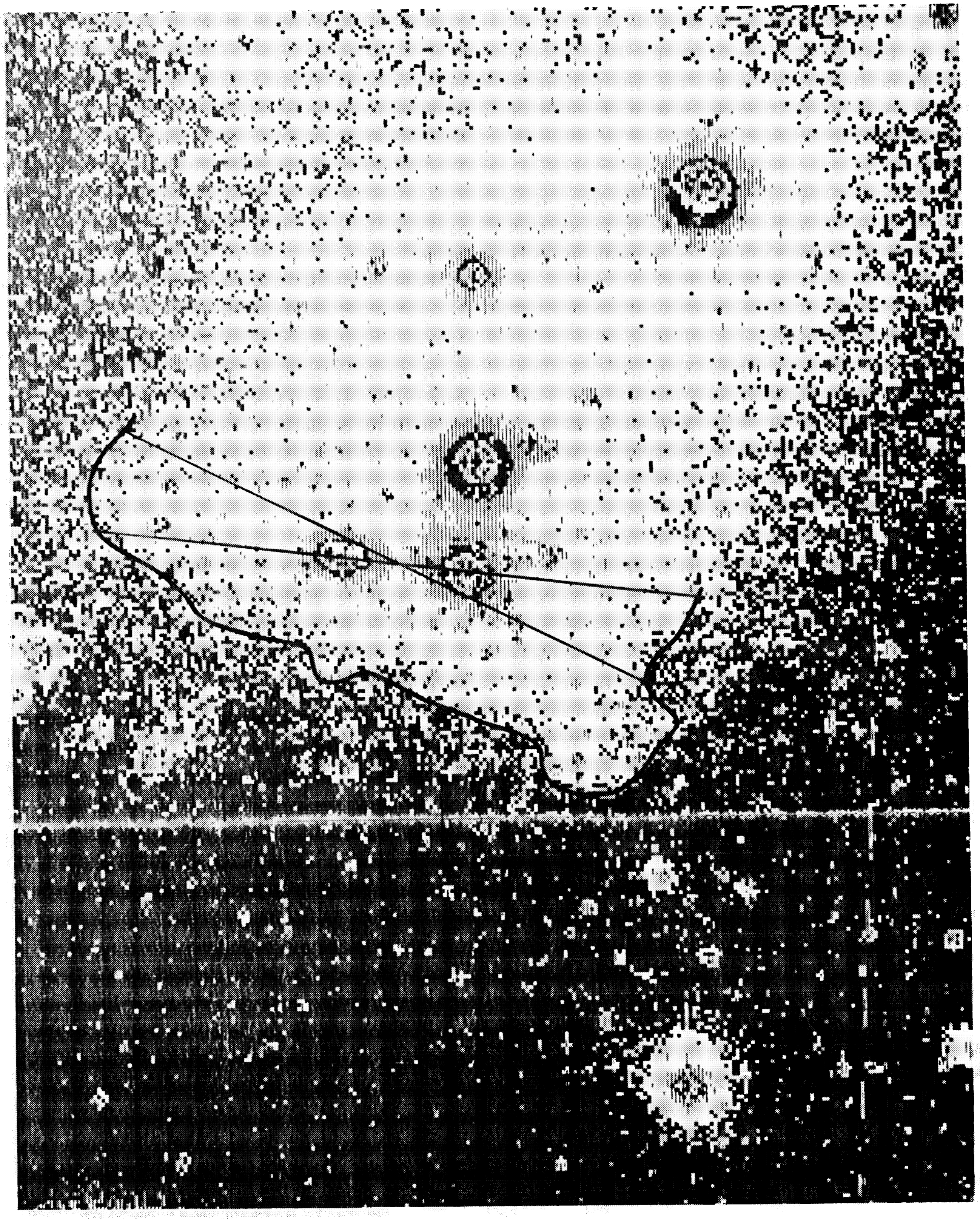

FIG. 1—Isodensity tracing of the central region of the Coma cluster. The heavy line shows the 27.24 $G\mu$ contour (E in Fig. 2). The areas were measured south of the two light lines, discussed in the text. This was the only IIIa-J plate used in this study, a 2^h15^m exposure with a Wr4 filter. We have corrected for the slight N-S background gradient. The scanning aperture for the tracing was 50×200 μm, and the density step-size was 0.1 D. North is at the top and east at the left, and the scale is 18.9 arc sec min^{-1}.

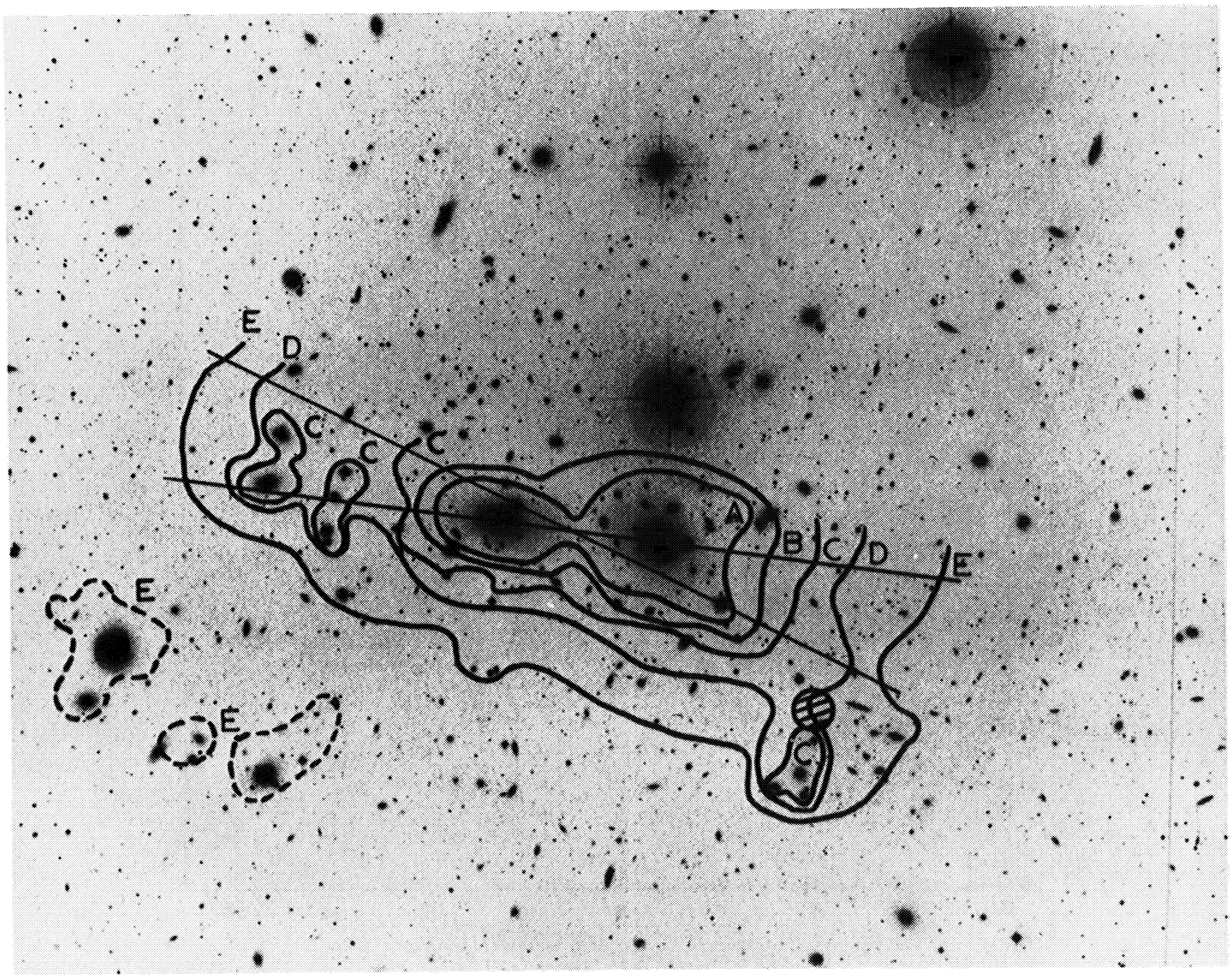

FIG. 2—Isodensity contours superimposed on a photograph of the Coma cluster. Approximate surface brightnesses detected are: A(25.73 $G\mu$), B(26.50 $G\mu$), C(26.79 $G\mu$), D(27.05 $G\mu$), E(27.24 $G\mu$). The dashed portions of contour E were not used, since they are not yet connected to the central isophote at this surface brightness. The straight lines are the same as in Figure 1. The shaded circle is the area measured photoelectrically by Mattila (1977) to have a brightness of 26.96 $G\mu$. The orientation and scale are the same as in Figure 1.

to $(B-V)$ with the standard transformations. Thus the B and G data give $(B-V) = 0^{m}.46$ for the background light, B and V imply $0^{m}.95$, and G and R give $1^{m}.00$. The mean of these values is $(B-V) = 0^{m}.80 \pm 0^{m}.30(\sigma)$. However, the fact that redder bandpasses imply redder colors suggests that the color correction to the star profile derived in Kormendy (1973), *which is based purely on a theoretical argument,* is slightly in error at long wavelengths. Thus a color bluer than $(B-V) = 0^{m}.80$ is most likely, consistent with Mattila's (1977) value of $0^{m}.54 \pm 0^{m}.18$ at one point in the cluster.

In Figures 3(a) and (b), mean lines have been drawn to define the profile shape. They are very similar. Also, both figures show as open circles the points obtained by Peebles (1974) from an independent reduction of three early Joyce-Loebl IDTs, using the same calibration technique. The excellent agreement with the present profile suggests that the results are not sensitive to the subjective details of the drawing of the contours. We will adopt for the background light the curve from Figure 3(b) (Table II).

Before discussing this profile, it is important to state precisely what it measures. The reason is that it is difficult to define what is meant by a cluster background. The key feature in our technique is that the isodensity contours essentially ignore light that is concentrated at a point, but measure only the smooth distribution of light over many pixels. Stars and individual galaxies appear in so few pixels that they only contribute to the sky noise. In particular, the density of stars is very similar in the cluster and near the calibrating stars, so

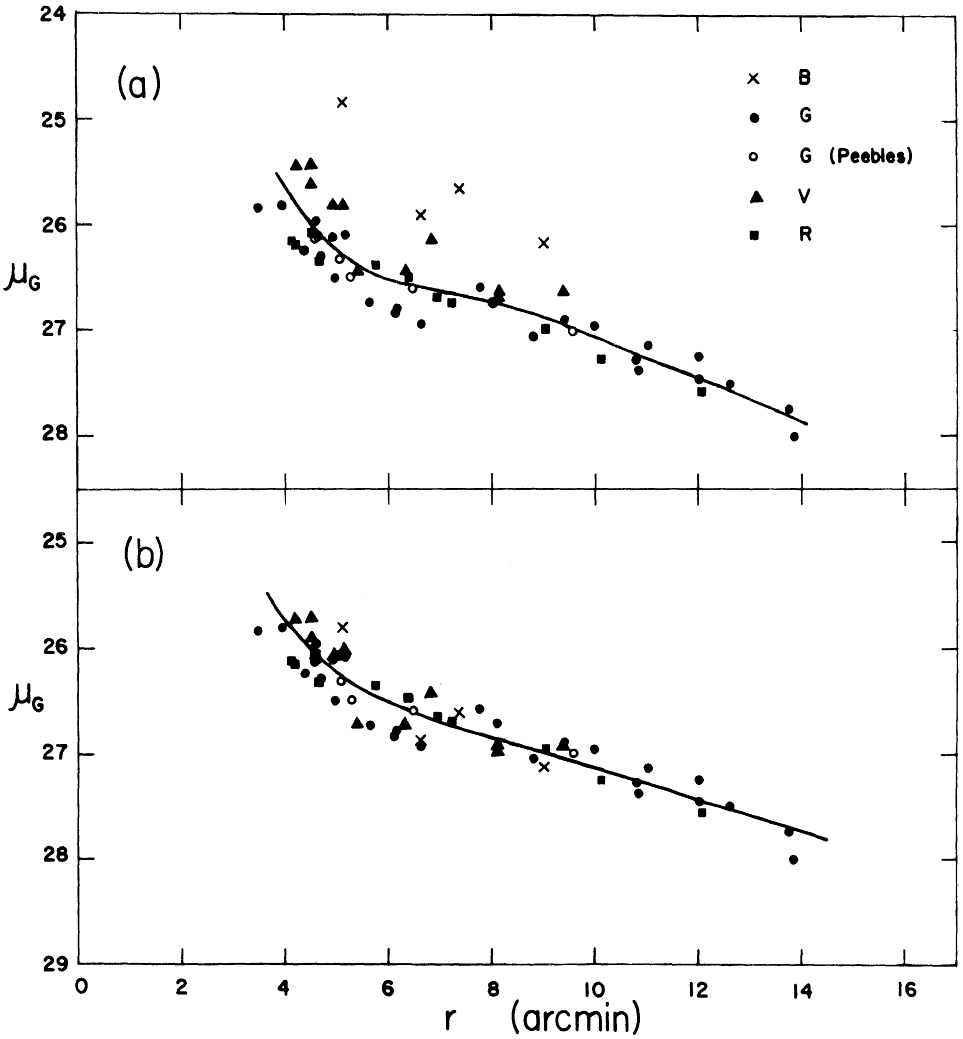

FIG. 3—G profile of the background light. In (a) the data in different colors have been vertically shifted to G using an assumed color index of $(B-V) = 1.03$ and the transformations given in section II. In (b) they have been shifted together to minimize the scatter. The line shown in (b) is the adopted profile.

that field stars are automatically removed. Small individual galaxies are also ignored. However, subgroupings of galaxies in common envelopes contribute strongly. The result is that at brightnesses $\lesssim 26$ $G\mu$, we are measuring mostly the profiles of NGC 4874 and NGC 4889. As the brightness detected becomes fainter, the contours expand and envelop more and more subgroupings of galaxies. By ~ 27 $G\mu$, most pixels are equally far from many individual galaxies, and thus are measuring light not associated with any particular galaxy. In this sense we are measuring intergalactic matter which we shall call the 'cluster background'.

One of the main aims of this study is to consider the agreement between different measurements of the background light. Mattila (1977) has made a photoelectric measurement of one area, shown in Figure 2, which was chosen to be free of galaxies. Converting his B and V magnitudes to G yields a brightness of 26.96 $G\mu$. Our isophotes indicate the same surface brightness to ~ 0.1 μ. Similarly, we can compare our results to the photoelectric data of MWH. A direct comparison with their Figure 2 is not possible because their isophotos have been smoothed with a large Gaussian beam ($\sim 4'$ FWHM). This has two effects. First, the large beam includes at least one galaxy between magnitudes 14 and 16 almost everywhere near the cluster center. Second, when centered on an isophote at ~ 27 $G\mu$, one side of the beam usually reaches to $\lesssim 25$ $G\mu$ on the side nearer the center. It is easy to show that either of these effects raises the local brightness by $\sim$ 1/2–1 μ. Thus the contours shown in their figure cannot be used to measure the distribution of light fainter than ~ 26 $G\mu$; the real isophotes have similar shapes, but are much fainter at any radius. This does not effect

TABLE II

BACKGROUND LIGHT IN THE COMA CLUSTER

(ASSEMBLED FOR MINIMUM SCATTER)

r (arcmin)	μ_G
4	25.70
5	26.25
6	26.52
7	26.70
8	26.85
9	27.00
10	27.10
11	27.25
12	27.40
13	27.57
14	27.75

any of the conclusions reached by MWH, which were all based on the unsmoothed data. Melnick et al. have kindly sent us their unsmoothed G data. We have analyzed this in the same way as our photographic data. This yields the closed squares in Figure 4. At the bright end, the pixels are still dominated by individual galaxies. In fact, ring counts by L. Schipper (1977) show that at 4 arc min radius approximately one pixel in four contains a galaxy with $V \leqslant 18.0$. Even fainter galaxies have a significant effect, since a brightness of 27 $G\mu$ over a 30 $\times$ 70 arc sec aperture corresponds to only an 18.7 magnitude object. However, at a radius of 10 arc min, only one pixel in ten contains a galaxy, and these can then be ignored in drawing contours. The MWH profile indeed converges approximately on our own at $\sim$ 27 μ (10 arc min). Apparently (1) they are then measuring the smooth background, and (2) the two sets of measurements agree reasonably well. Between 10 and 12 arc min, the MWH profile is 0.30 μ brighter than ours. This is within the combined errors of the two zero points. Most of the difference is produced by a correction to the sky brightness subtracted from the MWH profile, introduced in the final version of their paper (see §4ii). The change in the sky is only 28.9 $G\mu$, amply illustrating both the difficulty and the importance of the sky level determination. MWH also give, in their Table 2 an approximate profile of the "background light" in rings around the cluster center. This is somewhat fainter than the present profile, but the difference is not excessive in view of the large errors. A two-dimensional comparison of our IDT contours (Fig. 2), and MWH's isophotes (their Fig. 3) also shows qualitative detailed agreement. The data of de Vaucouleurs and de Vaucouleurs (1970) are more difficult to compare directly to our own because the form of the data is less similar, but we will see below that the total magnitude and the inferred fraction of light in the background are very similar. Evidently a body of reasonably consistent data is now available.

Next we compare the distributions of galactic and background light. To compare the profiles quantitatively, we have used data kindly communicated to us by L. Schipper (1977). These are ring counts of the number and luminosity of galaxies, which have been corrected for background galaxies by using radial velocity data and an analysis of the sky surrounding the cluster. The galaxy identifications and photovisual magnitudes are by Abell, the latter obtained by using extrafocal photographs (Abell and Mihalas 1966). The resulting profile of the light in galaxies is shown by open squares in Figure 4. Three similar measurements from MWH's Table 1 are also shown (open circles). The agreement between the two sets of data is good; we will adopt the mean line shown. We should note that the comparison of this curve to the background profile is not completely fair, because the galaxy data consist of ring counts while the background light is measured within irregular isophotes.

Two features are immediately apparent from Figure 4. (1) Above a brightness of $\sim$ 26 $G\mu$, the background light profile turns sharply upward, becomes the profile of the central supergiants, and therefore rapidly converges on the galaxy curve. (2) Fainter than $\sim$ 26 $G\mu$, the galaxy and background profiles are parallel within the errors. This suggests that the diffuse material is governed by the same potential as the galaxies, with no pronounced mass segregation, in agreement with MWH. This is consistent with the result of Rood et al. (1972) that the distributions of surface density and velocity dispersion of the galaxies can be explained by a self-gravitating model in which the gravitating mass is distributed in the same way as the test objects.

We turn now to the mass-to-light ratio problem, and the question of how much the background light may alleviate it. The total magnitude of the diffuse light in the "annulus" $4 \leq r \leq 14'$ is $G = 11.22$, or $B \doteq 11.89$. The corresponding luminosities are 1.7×10^{11} h^{-2} $L_{G_\odot}$ and $1.3 \times 10^{11} h^{-2}$ $L_{B_\odot}$. Here a velocity of

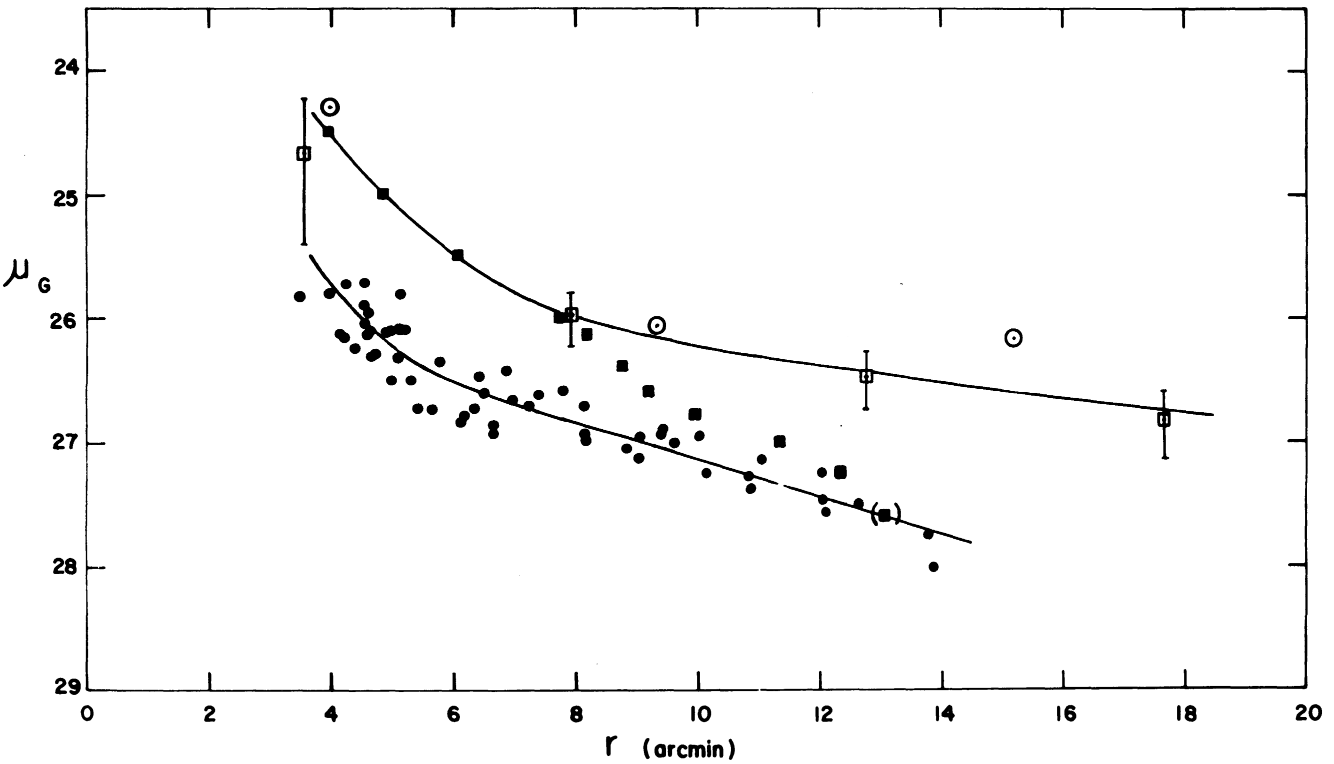

FIG. 4—Profiles of the background light (closed circles and lower curve), and of the light in galaxies (upper curve). The closed squares are from an analysis of the MWH unsmoothed photoelectric data. Note the convergence on the photographic profile at ~ 27 $G\mu$. The last point is in parentheses because a nonnegligible fraction of the isophote extends south of the strip measured by MWH; the measured area, and hence the equivalent radius are therefore too small. the open squares show the galaxy light profile from Schipper's ring counts and Abell's photographic magnitudes. The open circles are similar photoelectric data from MWH. The adopted mean curve for the three sets of points is parallel to the background profile, within the errors.

6947 km s^{-1} (Gregory and Tifft 1976) has been adopted, and h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. Galactic absorption has been neglected, and the adopted absolute magnitudes of the sun are $M_{B_\odot} = 5.8$ and $M_{V_\odot} = 4.83$ (Allen 1973). Integrating the adopted curve for the galaxies, and assuming their $(B-V) = 0.93$ (MWH), gives $G = 10.35$. Thus the smooth background contributes ~ 31% of the total light between 4 and 14 arc min. Locally this is a very significant luminosity, being ~ 45% of the amount of light in galaxies alone. However, as recognized by Rood et al. (1972) and others, it does little to help bind the cluster unless its mass-to-light ratio is abnormally high. Such a hypothesis is not supported by the blue color of the diffuse light. The present estimate of 31% of the light in the background is in reasonable agreement, within the errors of interpretation (which are probably larger than the errors of measurement), with the value of 40% obtained by de Vaucouleurs and de Vaucouleurs (1970).* Since this was the value used by Rood et al. (1972), their discussion of the mass-to-light ratio of the Coma cluster remains unchanged.

IV. Summary of Conclusions

We have measured the background light in the Coma cluster using a technique radically different from standard photographic and photoelectric photometry. The results, and previous measurements of various kinds, are in reasonably good agreement, so that statements about the distribution and luminosity of the

*The de Vaucouleurs and de Vaucouleurs (1970) estimate is a global one based on fitting models to both the background light and galaxy profiles, and calculating total magnitudes over the whole cluster. The present estimate is local, i.e., it uses only the light in the 4-14 arc min annulus. To compare our results more directly to de Vaucouleurs and de Vaucouleurs (1970) we have least squares fit a de Vaucouleurs law $\mu(r) = \mu_e - 8.325 + 8.325\,(r/r_e)^{1/4}$ to the data in Table II, excluding the central point. This yields $\mu_e = 29.8\ G\mu$ and an effective radius $r_e = 45'$ in good agreement with the value $r_e = 50'$ derived from surface photometry by de Vaucouleurs and de Vaucouleurs (1970) and from Zwicky's galaxy counts by de Vaucouleurs (1948). The corresponding total G magnitude is $-2.5 \log(7.268\pi_e r_e^2) = 9.2$. If $(B-V) \simeq 0.8$, then $B = 9.7$, which agrees well with the estimate from the above paper, $B = 10.0 \pm 0.5$.

background light can now be made fairly securely.

Both the detailed isophotes and the equivalent profile of the diffuse light follow the corresponding distributions for galaxies very closely. There is no sign of mass segregation in the present data, though there is evidence for a population gradient in that the background may be bluer than the galaxies. A photoelectric observation by Mattila (1977) of one area free of galaxies also shows the diffuse light having a bluer color ($(B-V) = 0.54 \pm 0.18$) than the galaxies.

What is the source of the diffuse light? The observed color is inconsistent (too blue) with the diffuse light coming from thermal bremsstrahlung from a hot ($T \sim 10^6$ K) intergalactic gas (Mattila 1977). Our observations and several other lines of evidence are consistent with the hypothesis that the background light comes from stars tidally stripped from the outer parts of galaxies. Generally, galaxies are observed to become bluer at larger radii (e.g., de Vaucouleurs 1961; Strom et al. 1976; Strom et al. 1977). In fact, at brightnesses similar to the ones observed here, M87 has a $(B-V)$ color of ~ 0.6 (de Vaucouleurs 1969), consistent with the color of the Coma background light. However, within 25 arc min radius of the center of Coma, only 3 of 42 bright ellipticals observed by Strom (1976) show color gradients, while at larger distances from the center, the number of galaxies possessing color gradients increases. These observations suggest (but do not prove) that the blue outer halos of the central galaxies in Coma have been tidally stripped in the frequent galaxy collisions occurring near the center of the cluster, and have been spread out into the observed blue background light.

The total background light between 4 and 14 arc min (26 and 28 $G\mu$) is $G = 11.22$, or $\sim 45\%$ of the light in galaxies, or $\sim 31\%$ of the total light in the annulus. De Vaucouleurs and de Vaucouleurs' (1970) background correction, used in the $\mathfrak{M}/L$ study by Rood et al. (1972), is essentially confirmed. Thus there is still no sign of enough mass in visible light to bind the cluster.

Finally, we should note that all current estimates of the background light are lower limits in the sense that the sky brightness is measured at $\sim 1° - 2°$ from the center. A smooth distribution with a gradient much shallower than that of the galaxies, but with a radius similar to that of the cluster, would have remained entirely undetected and would reduce the observed $\mathfrak{M}/L$ drastically.

This study was suggested by Dr. P. J. E. Peebles, who reduced some early Joyce-Loebl tracings to make preliminary estimates of the background profile and luminosity. It is a pleasure to thank Dr. Peebles for his continued interest, and for helpful conversations. We thank the Director of the Hale Observatories for observing time on the Palomar 48-inch telescope, and Dr. J. N. Bahcall for kindly taking a plate for us. Both authors were at Caltech when the measurements were carried out. We are most grateful to the Berkeley Astronomy Department for permission to use their PDS microdensitometer, to Dr. H. Spinrad for arranging a visit of T.X.T. to Berkeley, and to Dr. I. King and Mr. R. Kron for technical and programming assistance with the PDS. We thank Mr. L. Schipper for letting us use his ring counts before publication. Helpful conversations with Mr. J. Hoessel and Drs. J. Melnick and S. Strom are also acknowledged. J.K. is supported at Berkeley by a Parisot postdoctoral fellowship.

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