CCD OBSERVATION OF DIFFUSE LIGHT IN THE RICH CLUSTER A2029

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ABSTRACT. By mosaicking many CCD frames together, we have constructed a large-scale (~ 1/2°) R-band map of the cD cluster Abell 2029. The map was flat from one edge to the other to about 0.05% of the night sky, which corresponds to $\nu_R \sim 30$ mag arcsec^2. Using a novel technique involving the pixel distribution function, we measured diffuse light in the cluster out to 450″ (500 h^{-1} Kpc) along the minor axis of the cluster. In the elliptical region from minor radius 100″ to minor radius 300″, the diffuse light corresponds to roughly 8% of the total cluster light. Data in other optical bands and on other clusters are in the process of being reduced. The applicability of the above technique to measurements of the fluctuations in the extragalactic background light (EBL) is discussed.

1. INTRODUCTION

Guhathakurta, Tyson, and Partridge have discussed at this symposium observations of diffuse optical light with CCD's. I am going to discuss an ongoing effort of Jeff Kuhn, Juan Uson, and myself to measure the diffuse intergalactic light in rich clusters of galaxies. It has been predicted (see review by Dressler, 1984) that the cluster tidal force will strip a substantial amount of matter, including stars, from the outer portions of cluster galaxies and that the dynamics of this matter will be determined by the cluster potential. As a result, a substantial fraction (~ .1 to .4) of the total cluster light will be in the form of diffuse intergalactic light. Since clusters are quite extended and the field of view provided by most CCD's is quite small, it was necessary to make a mosaic map consisting of many overlapping CCD frames.

Jeff Kuhn and I first realized the potential for making extended CCD frame maps when, as a followup to 2.2 μm measurements, we made a 32-frame R-band map of the dark molecular cloud, L134. We were attempting to deduce the extragalactic background by using the cloud as a way to subtract foreground light (Mattila, 1976). Of course, we found that the cloud was not dark and its luminosity exceeded that of nearby patches of blank sky. The darkest portions of the cloud had intensities, νI_ν, of 1×10^{-5} ergs cm^{-2} s^{-1} sr^{-1} at 0.65 m and 4×10^{-5} ergs cm^{-2} s^{-1} sr^{-1} at 2.2 μm, indicating that either the EBL is on the order of or smaller than these values or that the reflected light and EBL cancel fortuitously (Boughn and Kuhn, 1986).

From the R-band map, it was evident that mosaic CCD maps could be made for which large-scale systematic errors are below 0.2% of the night sky brightness. An obvious application of this technique is mapping the diffuse light in rich clusters of galaxies.

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2. CCD R-BAND MAP OF A2029

A 16-frame, mosaic R-band CCD map of the Abell cluster A2029, taken with the RCA3 chip at the KPNO #1 36" telescope, is depicted in Figure 1. The extended halo of the central cD galaxy can be easily traced out to 2′ (150 h^{-1} Kpc) along the major axis, as can be seen in the contour plot of Figure 2. This area is completely contained in the single central CCD frame.

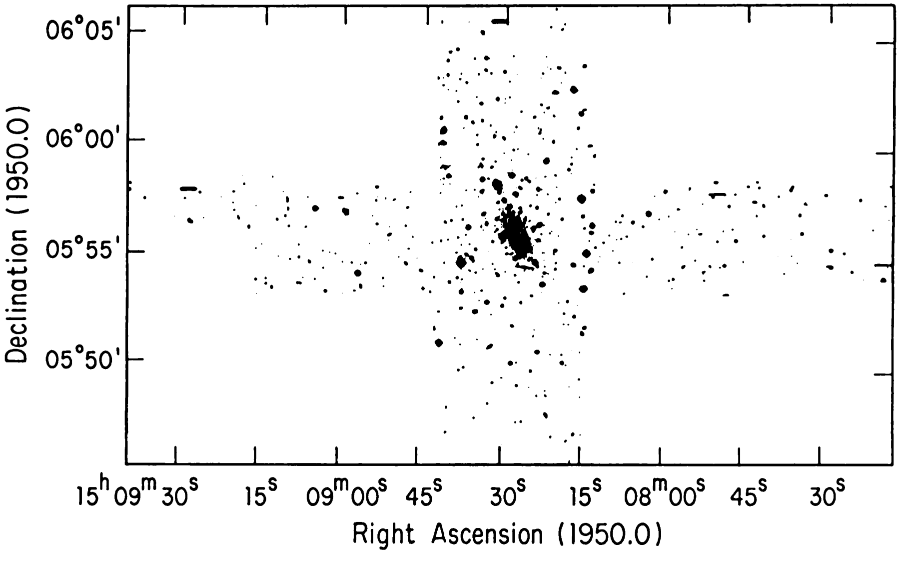

Figure 1. Mosaic of A2029 made from 16 overlapping CCD frames.

The sixteen frames were flat-fielded from a median average of 16 nearby blank field frames and combined by the following method. A 3σ cut was applied to each frame to find objects with surface brightness ≥ 8% of the night sky, and two sets of image frames were formed, one with only the objects and one with the objects excluded. The alignment of the frames was accomplished by a least-squares-fit to the object frames in their overlap regions which were typically half a CCD frame. The difference in overall sky level was determined by a least-squares-fit to the overlap region of the object-free frames. The mosaic was formed by adjusting the position of each original frame accordingly and by adding an offset to each frame to correct for sky level variations. No lines at the boundaries of individual frames are apparent even on high-contrast representations of the map.

3. THE PIXEL DISTRIBUTION FUNCTION AND DIFFUSE LIGHT DETERMINATION

Since the diffuse halo of the cD has an ellipticity which is unchanging with distance out to the contours measured (see Figure 2), the map was divided into elliptical bins, and the diffuse light determined in each elliptical bin. Rather than the standard procedure of eliminating sources and averaging the light from the remaining area, we constructed a luminosity histogram for each elliptical bin. A Gaussian was then fit to that portion of the histogram below the peak

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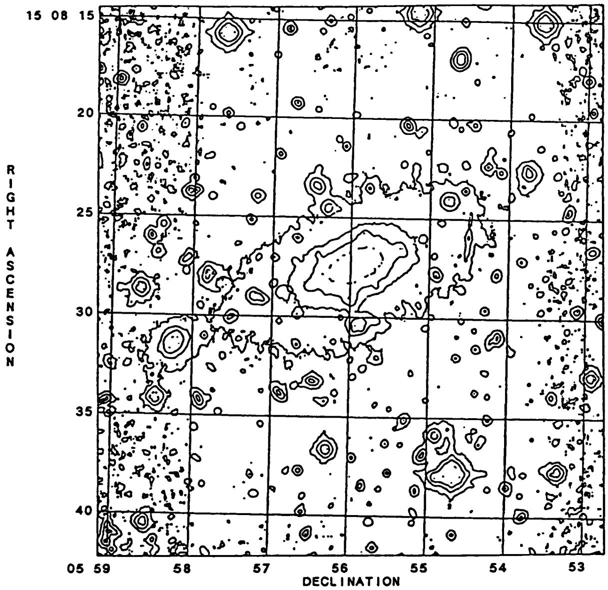

Figure 2. Brightness contours of the cD in A2029. The outer contour corresponds to μ_R = 23.5.

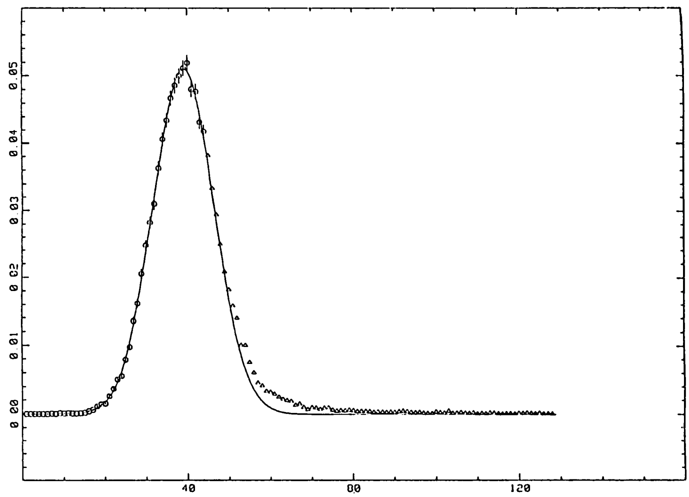

Figure 3. Pixel luminosity histogram. The vertical axis is fraction of total pixels, and the horizontal axis is luminosity per pixel in arbitrary units. The brightness of the night sky is equivalent to 145 of these units.

plus $1/2\sigma$. The diffuse light was taken to be the mean value of the fitted Gaussian. Figure 3 shows a typical histogram and fitted Gaussian. Pixels which fall in bright objects do not bias this value because they lie far to the right on the histogram. Figure 4 shows the histograms for 60 bins. The bottom histogram is about 30″ from the center of the cluster, and the top is at the edge of the field, about 15′ from the center. Only the data from the east-west strip were

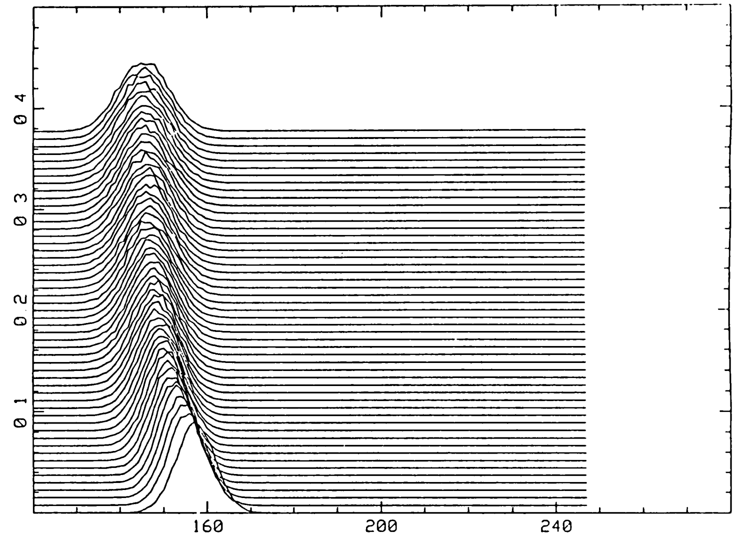

Figure 4. Luminosity histograms for 60 distance intervals located 30″ to 15′ from the center of the cD. Units are the same as in Figure 3 with arbitrary offset.

analyzed because of cloud contamination of the north-south strip. (A paper by Stüwe presented at a poster session of this symposium uses a similar method to detect the light scattered from high latitude dust clouds.)

The non-Gaussian tail evident in the histograms is probably due to the halos of individual galaxies. A Monte Carlo simulation of the cluster using a Schecter luminosity function (Schecter, 1976) and the galaxy profiles of Binggeli, Sandage, and Tarenghi (1984) gave similar results. These calculations also indicated that galaxy halos slightly bias the mean of the fitted Gaussian, i.e., the diffuse light estimate, so the data were reanalyzed after four successive 3σ cuts, followed by a doubling of the radius of the excluded region around all objects. This reduced by about 30% the diffuse light values discussed in the next section. Monte Carlo simulations (Berlin, 1988) indicated that these cuts were sufficient. In addition, increasing the excluded regions around the objects did not change the values, so we conclude there is no systematic bias of our estimates.

4. DIFFUSE LIGHT IN A2029

Figure 5 indicates the value of the diffuse light in A2029 expressed in percentage of the night sky from east to west across the frame. The fact that beyond 500″ the background sky is flat and equal on both sides of the cluster indicates that we have reached the edge of the cluster and have successfully flat-fielded the frame across the entire 30′ strip. Even though the cluster is somewhat asymmetrical, we folded the data about the center, and the average profile expressed in distance along the minor axis is plotted in Figure 6. Full scale is 1% of the night sky, and the smallest error bars correspond to $< 0.05\%$ of the night sky. About 1/3 of this noise is due to photon shot noise, 1/3 is due to CCD readout noise, and 1/3 is unaccounted for.

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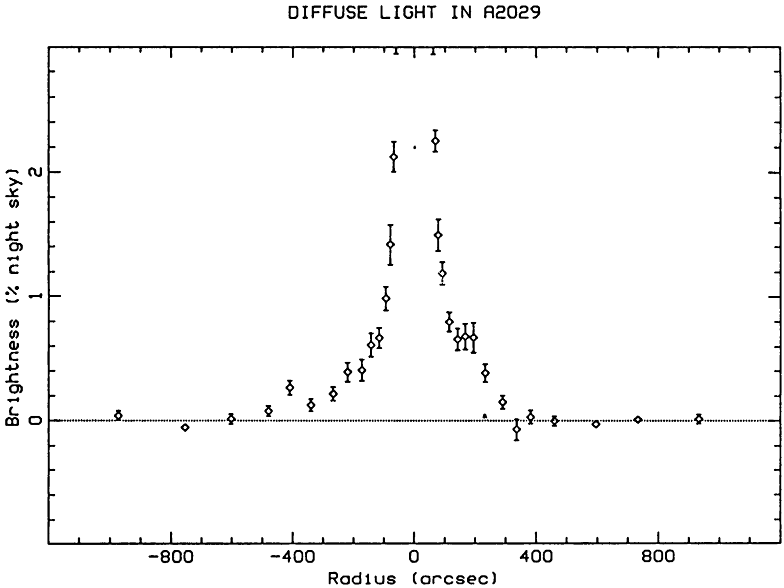

Figure 5. Brightness of the diffuse light as a function of minor radius. Error bars represent statistical errors of the fit; – corresponds to east and + corresponds to west.

The average night sky level was about $\nu_R = 21.0$ mag arcsec^{-2}, which corresponds to roughly $\nu I_\nu \sim 3.5\times10^{-3}$ ergs cm^{-2} s^{-1} sr^{-1} . Frames were taken of several Landolt UBVRI standards, and the overall calibration is estimated to be accurate to a few percent.

It is clear from Figure 6 that diffuse light is detected out to about 450″ along the minor axis of the cD. This corresponds to a distance of 500 h^{-1} Kpc and an equivalent distance of 1 h^{-1} Mpc along the major axis. Outside of this distance the diffuse light is constant within a surface brightness of about $\mu_R \sim 30$, which corresponds to $\nu I_\nu \sim 10^{-6}$ ergs cm^{-2} s^{-1} sr^{-1}.

In order to compare our diffuse light measurements with Dressler's (1979) surface photometry of the central cD, we projected his measurements on the minor axis and translated them to the R-band using V–R = 0.7. Figure 7 illustrates this comparison.

Preliminary analysis of stellar frames indicates that the point spread function (PSF) of the central cD does not significantly contaminate our diffuse light measurements. However, these results should be considered preliminary until a proper account of the PSF can be taken, i.e. convolving individual sources. It is possible that the extremities of the PSF for several bright stars in the field could account for some of the asymmetry in the diffuse light brightness profile.

5. DISCUSSION

Although the data presented in this paper are preliminary, it is clear that we have detected diffuse light in A2029 out to about (0.5–1.0) h^{-1} Mpc, which corresponds to ~ 3 core radii. The total diffuse light between 100 and 300″ minor axis distance is roughly 8% of the total

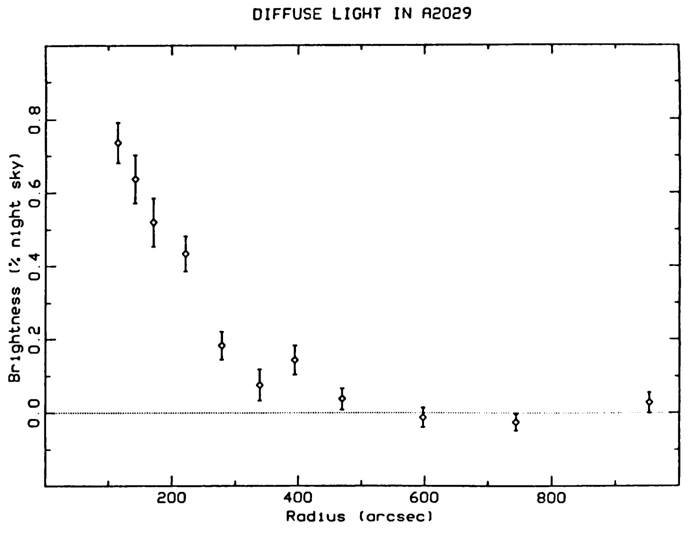

Figure 6. Same data as Figure 5, folded about the origin, averaged, and plotted on an expanded scale.

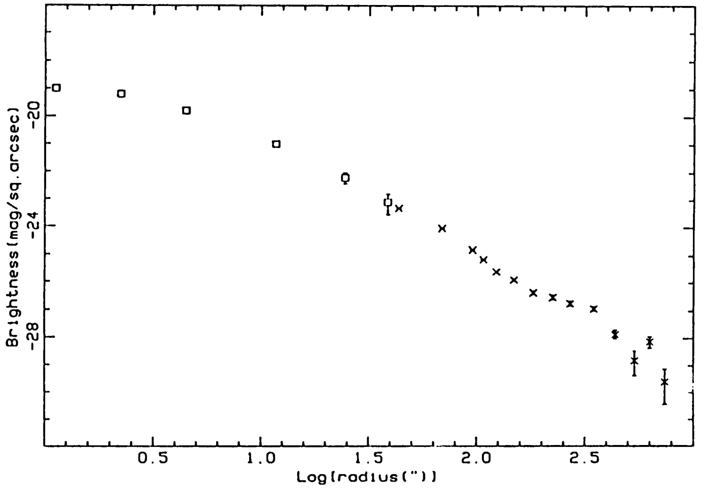

Figure 7. Comparison of cD surface profile of Dressler (1979) with this work. In order to compare directly, Dressler's data have been shifted by V − R = .7 and projected onto the minor axis. The squares represent Dressler's data, and the crosses are from the present observations.

cluster light (this fraction will be computed more accurately later), which is somewhat smaller than most tidal stripping calculations predict. We are currently analyzing data taken in B-band and V-band filters and on other clusters. These data should help determine the nature of the diffuse light we detect.

From the velocity dispersion measurements of Dressler (1981), we estimate a mass-to-light ratio of the dark matter of about (M/L) ~2000 h^{-1} in solar R-band units between 160 and

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620 h^{-1} Kpc, provided that the dark matter is distributed roughly as the diffuse cluster light. If the dark matter is derived from a main-sequence luminosity distribution, this value strongly constrains these stars to the late end of the main sequence; however, the 2 μm measurements of Boughn and Uson (1987) provide stronger constraints.

An important result of our present measurements is that large-field (~ 1°) mosaics can be made that are flat to $\mu_R \sim 30$. This technique might be applied to "blank" fields in order to search for fluctuations in the extragalactic background on scales from 1′ to 1°. As Peebles pointed out at this symposium, the best measurements on this scale are still those made by Schectmann (1974).

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P. Guhathakurta: *In matching sky levels between different CCD mosaic frames — would it be useful to use compact objects along with sky pixels? If airmass varies between frames, would extinction variations make it necessary to match the levels multiplicatively, as opposed to additively?*

S. Boughn: I think not. At any rate we were more worried about variations in seeing which argues against using compact objects.

G.F.O. Schnur: *Could you not have used a small, wide field telescope to avoid having to combine the mosaic?*

S. Boughn: Yes. However, the wider the field the lower the resolution and as a result more small, discrete sources would be mistaken for a diffuse background.