Reports

The Central Galaxy in Abell 2029: An Old Supergiant

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A mosaic of images shows the extended structure of the cD galaxy that resides at the center of the rich cluster of galaxies Abell 2029. After correcting for the scattered light of nearby stars and galaxies, the faint halo of this giant can be traced out to a distance of more than 1 megaparsec, making it one of the largest and most luminous galaxies known. The smoothness of this halo suggests that it was formed early in the history of the cluster.

Most of the galaxies in the universe are clustered and galaxy clusters themselves are organized into superclusters in hierarchical structures of increasing scale to perhaps 100 Mpc [1 parsec (pc) ~ 3×10^{16} m] (*1*). Unfortunately, we know even less about how clusters evolve than we do about galaxy evolution. Even questions as fundamental as whether galaxies or clusters form first are not resolved. A number of clusters are unusual in that they contain a dominant galaxy located at the center of the galaxy distribution and which often emits a significant fraction of the total cluster light. These cD clusters are interesting because the evolution of the dominant cD galaxy and that of the cluster itself must be tightly coupled (*2*).

The evolution of clusters of galaxies depends on galaxy collisions and tidal disruption of their outer regions. These processes may release a large amount of matter, including stars, into intergalactic space. Indeed, theoretical simulations predict that up to 70% of the initial cluster mass was released into the intergalactic medium as the cluster evolved (*3*). This "stripped" matter ought to be observable as diffuse intergalactic background light.

Observations of diffuse light require enough spatial resolution to distinguish a diffuse component from a blend of faint cluster galaxies and foreground stars. This requires observing relatively nearby clusters ($Z \leq 0.1$) in order to achieve a resolution of about 1 kpc. Since these galaxies and their extended halos are large we must also observe wide angular fields. Photographic plates satisfy this requirement but, in general, are limited by their inhomogeneities as well as the nonlinear response of the emulsions. Modern charge-coupled device (CCD) cameras successfully overcome these problems, but have a limited field of view. Our solution has been to carefully combine a number of CCD observations into a single wide-field measurement that maintains photometric "fidelity" across the entire composite field. This technique allows us to measure the diffuse light at the level of 2×10^{-4} of the average brightness of the night sky (*4*).

We have made a mosaic image of the cluster Abell 2029 from 16 overlapping exposures made with the RCA #3 CCD camera on the #1 36-inch telescope at Kitt Peak National Observatory. (Fig. 1). The image is 34 arc min by 21 arc min in size with a cross pattern that samples the center and outer parts of the cluster. The large central bright object is a cD galaxy and most of the smaller objects are galaxies in the cluster. The resolution is 0.86 arc sec per picture element (pixel) which corresponds to 2.5 kpc at the distance of the cluster (470 Mpc, assuming a value for Hubble's constant of 50 km s^{-1} Mpc^{-1}). This is adequate to distinguish the diffuse light in the cluster from galaxies and foreground stars. A global least-squares solution was used to match the intensity and registration of individual frames. Although the average night sky level varied by ±30% during the course of our observations, these large spurious intensity offsets were removed by the analysis procedure. The calibration and other systematic errors are below 2×10^{-4} of the average sky level.

The noise associated with each pixel in any one of the 16 frames is relatively large, about 5% of the night sky level, so a measurement of low-level diffuse light must involve averaging the light from a great number of pixels. In doing this one must carefully avoid pixels which contain light from galaxies and foreground stars. We have devised an objective statistical technique in which diffuse light is inferred from the intensity distribution of the pixels. The high-intensity pixels associated with objects fall in the tail of the distribution and do not bias our estimate of the diffuse light. This technique is described in detail elsewhere (*4*).

It was first emphasized by King (*5*) that the telescope optics and atmospheric scattering combine to spread about 5% of the light of any object beyond 30 arc sec from its actual position. We have spent considerable time measuring the Point-Spread-Function (PSF) of the telescope. We have used this PSF to remove the scattered light from the 45 brightest stars located within 20 arc min of the cluster center as well as the scattered light from the cD galaxy itself.

The inner light contours of the cD galaxy are elliptical with a 2:1 axis ratio, which is

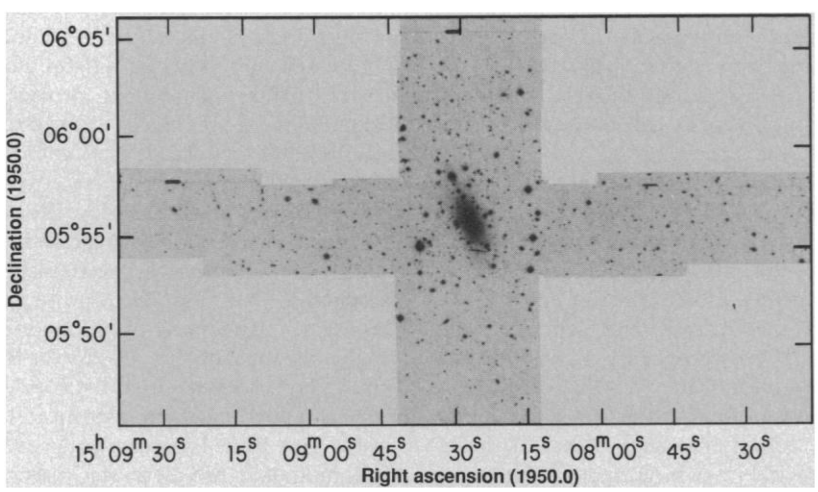

Fig. 1. A 16-frame mosaic of Abell 2029 and its surrounding region. Except for the uneven boundary, the picture does not have the appearance of a composite of exposures taken with a variable sky level.

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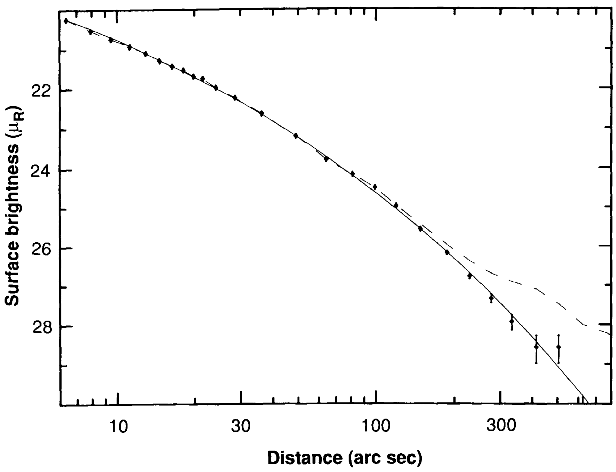

Fig. 2. The surface brightness of the diffuse light (in R-band magnitudes per square arc second) in Abell 2029 plotted as a function of distance along the major axis of the elliptical annuli. One arc second corresponds to 2.25 kpc. The solid curve is a fit of the deVaucouleurs function to the plotted data. The dashed curve is the light profile which we actually observed (that is, uncorrected for scattering). The average brightness of the night-sky emission was $\mu_R = 21.0$ during our observations.

independent of distance from the center. The statistical analysis of the diffuse light discussed above was done using several different geometries. We found that the width of the pixel-intensity distributions was minimized using the same geometry as that of the cD galaxy and was consistent with our expected measurement noise. Consequently, the diffuse light has an elliptical profile with the same axis ratio and orientation as that of the cD galaxy. The diffuse brightness is plotted in Fig. 2. It is well known that the surface brightness profile of elliptical galaxies tends to follow a functional form that was first expressed by deVaucouleurs (*6*). Two points are immediately apparent: (i) The outer (faint) part of the galaxy profile must be corrected for the diffuse large angle scattering from bright stars, and (ii) the deVaucouleurs function describes the data as far out as we can measure the profile. As shown in Fig. 2, this two-parameter function is a very good description of the surface brightness of the cD galaxy from a few kiloparsec to over 1 Mpc from its center. We see no significant deviations from the smooth deVaucouleurs profile. Indeed, the statistical distribution of the pixel surface-brightness measurements in each elliptical bin is consistent with our expected measurement noise. Moreover, there is no evidence for clumpiness in this diffuse component at a level of a few percent.

Whether the diffuse halo in Abell 2029 is considered to be an extension of the central cD galaxy or a component of diffuse cluster light is, to some extent, a matter of semantics. However, three considerations lead us to favor the former description: (i) the light profile is well described by a smooth two-parameter function over the entire range where we can measure it; (ii) the ellipticity of the halo is the same as that of the cD galaxy within our measurement errors; and (iii) the diffuse halo is distributed in a different way than the galaxies in the cluster. Indeed, the ratio of diffuse light to total cluster light evaluated in the same elliptical bins decreases steadily from a value of 1 at the cluster center to 0.05 at the farthest elliptical bin where the halo can be measured (*4*). Quite simply, the central galaxy is indistinguishable from the diffuse light that extends over 1 Mpc from the cluster center. Thus, this "object" is among the largest and most luminous galaxies observed. It has a luminosity of $2 \times 10^{12} L_\odot$ (where $L_\odot$ is the luminosity of the sun in this band) and an elliptical shape with axis ratio 2:1 and semimajor axis of at least 1.2 Mpc. Approximately 26% of the total light from the cluster is emitted by this giant galaxy.

Earlier measurements (7) have shown that A2029 is one of the densest clusters known with a line-of-sight velocity dispersion $\sigma_V = 1430$ km s^{-1}. Its mass-to-light ratio in the V-band is about 500 in solar units (that is, the ratio of the mass of the cluster to its luminosity is 500 times that of the sun). This means that A2029 is one of the most extreme examples of the "dark matter" problem. X-ray observations of the cluster (*8*) also argue for vast amounts of unseen matter. Since the dark matter should be smoothly distributed in the cluster, the mass-to-diffuse-light is a more meaningful quantity. If the diffuse component provides the dynamically inferred mass, its mass-to-light ratio is 3900 (in solar R-band units) in the elliptical annulus between (major axis) distances of 700 kpc and 1.2 Mpc. We can use our upper limits on the diffuse component in the elliptical annulus between (major axis) distances of 1.2 and 2.4 Mpc to place a lower limit on the mass-to-light ratio of the unseen mass of 9000 (again in solar R-band units). These values exceed the corresponding ones for any main sequence star no matter how faint. For example, the mass-to-light ratio of an M8 dwarf star is about 700 and even the most extreme main sequence star, VB10, is believed to have a mass-to-light ratio of about 4400 (*9*). Therefore, the dynamically implied mass cannot be composed of hydrogen-burning stars. It is most likely that the diffuse light we have measured is emitted by main sequence stars which contribute only a small fraction of the mass of the cluster; therefore, the "dark matter" remains undetected.

The large spatial scale of the diffuse light is a clue to the formation of the galaxy. Was the galaxy formed early in the evolution of the cluster, or is it a result of ongoing galaxy mergers and close encounters that strip stellar material from galaxies into the cluster medium? It would be difficult to produce a smooth diffuse background if it were a consequence of ongoing interactions between the cluster galaxies as mass liberated into the cluster through galaxy collisions will be clumpy. Since the typical particle velocity in the cluster potential is about 1500 km s^{-1}, the time scale for material diffusion is a few billion years so that the clumps would not have had enough time to smooth themselves out. However, the light distribution in the elliptical bins between minor axis radii of 1 and 3 arc min shows no statistically significant departure from the smooth deVaucouleurs law at a level of (standard deviation) about 5%. This excludes the possibility of significant ongoing stripping and is consistent with the arguments of Merritt (*10*) who also concluded that the dominant cD galaxies in clusters are a result of the primordial relaxation phase of the cluster.

The central galaxy in Abell 2029 is remarkable for its size as well as the uniformity of its structure. Both of these characteristics suggest that its birth must have occurred during the initial formation of the cluster.

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