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A triple nucleus in the brightest cluster galaxy in Abell 193

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ABSTRACT

We present a ground-based, near-infrared, *K*-band image and a *Hubble Space Telescope* (*HST*) WFPC2 image of the brightest cluster galaxy in Abell 193 (IC 1695). This object was selected as the central cluster galaxy using X-ray information. Both images reveal a triple nucleus structure. Previously, this galaxy was thought to have only two nuclei. We present colours and magnitudes and a colour plot of the three nuclei. The nuclear structure and colours of the nuclei in this galaxy suggest that a merger may have taken place in its recent history.

Key words: galaxies: clusters: general – galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: individual: IC 1695 – galaxies: nuclei – galaxies: structure.

1 INTRODUCTION

Our picture of the central structure of galaxies has evolved significantly over the last decade, due to the high-resolution capabilities of the *Hubble Space Telescope* (*HST*) and ground-based facilities with active and adaptive optics. Optical observations using WFPC2 have enabled detailed analysis of the cores of elliptical (Lauer et al. 1995; Byun et al. 1996; Gebhardt et al. 1996; Faber et al. 1997; Graham et al. 2003) and spiral (Carollo et al. 1997; Carollo, Stiavelli & Mack 1998; Carollo & Stiavelli 1998) galaxies, with extension to near-infrared wavelengths using NICMOS (Carollo et al. 2001, 2002; Seigar et al. 2000, 2002; Balcells et al. 2003; Fathi & Peletier 2003).

Nuclear investigations of elliptical galaxies, to date, have concentrated on normal ellipticals with no attempt to understand properties of giant ellipticals. Of a sample of 57 elliptical galaxies, Lauer et al. (1995) included only six giant elliptical galaxies and say little about their properties. A more recent study by Laine et al. (2003) used *HST* to study a sample of 81 giant elliptical galaxies to study their nuclear morphologies. The *HST* image presented in this paper was obtained as part of the the snapshot program on which the Laine et al. (2003) study is based. The nuclei of giant elliptical galaxies are of interest, because these galaxies tend to lie at the centres of clusters as the brightest cluster galaxy (BCG). About half of all BCGs have companions, or a secondary nucleus, located within a projected radius of 10 h^{-1} kpc ($H_0 = 100\ h$ km s^{-1} Mpc^{-1}) of the luminosity centre of the combined system (Hoessel & Schneider 1985). Chance projections of background or foreground cluster galaxies into this radius are expected to occur only about 10 per cent of the time for a cluster of richness class 2 (Tonry 1984). Thus there is a real excess of galaxies near first-ranked cluster members; no similar excess exists around the second or third ranked galaxies (Schneider, Gunn & Hoessel 1983). Abell 193 has a richness class of 1, and therefore the chance of foreground or background projections will be slightly lower.

These 'multiple nuclei' were at one time taken to be the best evidence for models which postulate that massive galaxies are growing at the centres of rich clusters by accreting, or 'cannibalizing', their less massive neighbours (Hausman & Ostriker 1978). The major difficulty with this interpretation is that the radial velocities of the secondary concentrations relative to that associated with the centre of the underlying BCG light distribution are typical of randomly selected cluster galaxies (Jenner 1974; Tonry 1984, 1985). These high velocity differences imply that the 'nuclei' are generally not bound, and are, therefore, not candidates for imminent cannibalism (Merritt 1984).

In this paper we report the discovery of a triple nucleus in the centre of IC 1695, the BCG in Abell 193. IC 1695 was identified as the BCG in Abell 193, optically by Lauer & Postman (1994), and using X-rays by Lynam et al. (2000). This galaxy was previously only thought to contain two nuclei (Hoessel & Schneider 1985). We present two images, revealing a triple nucleus, one in the near-infrared *K* band, taken from the ground with the 3.8-m UK Infrared Telescope (UKIRT) on Mauna Kea, Hawaii, and the other taken with WFPC2 on *HST* with the F814W (i.e. *I*-band) filter. We also present spectra taken with UKIRT. The spectra were used to calculate the redshifts of the three central components. We then discuss the possibility of this being the result of a merging system.

This paper is arranged as follows. In Section 2 we report the observations; Section 3 is a discussion of the results of these observations; Section 4 is a discussion of the interpretation of nuclear characteristics in galaxies; and Section 5 summarizes our conclusions.

2 OBSERVATIONS

We have obtained a near-infrared *K* band (2.2 μm) image of the BCG in Abell 193 (IC 1695). This image was observed at the 3.8-m

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UK Infrared Telescope (UKIRT) with the UKIRT Fast Track Imager (UFTI) on 2002 July 30. UFTI is a 1024 × 1024 Hawaii array with a pixel scale of 0.091 arcsec. A total of nine frames were observed with an individual exposure time of 60 s. A 9-point jitter pattern was used with offsets of ∼20 arcsec between each frame, in order to facilitate cosmic ray and bad pixel removal. After dark subtraction, each frame was flat-fielded using interspersed sky frames of equal integration time to the science frames. The flat-fielded frames were then masked for bad pixels and sky-subtracted. The final frames were then combined to provide a single image of effective integration time 9 min. At the time when this image was taken, the seeing was extremely good with full width at half maximum (FWHM) ≃0.35 arcsec.

We have also retrieved a WFPC2 image of this galaxy from the *HST* archive. The image was taken with the F814W (*I*-band) broad-band filter and was centred on the PC with a pixel scale of 0.046 arcsec. A total of two frames were observed and combined in order to remove cosmic rays. The exposure time of the combined image was 1000 s.

We have also obtained *K*-band spectra of the three nuclei using CGS4 on UKIRT. The spectra were obtained on 2002 December 4. The integration times were scaled so as to get approximately the same signal-to-noise ratio for each nucleus. The integration time on the brightest nucleus was 60 min, on the next nucleus 90 min and the final nucleus was observed for 100 min. The slit was oriented east–west (E–W), such that light from only one nucleus fell in the beam. The central wavelength was 2.2 μm and the 40 line mm^{-1} grating was used with a 0.6-arcsec slit. This resulted in a resolving power of ∼800.

3 RESULTS

Fig. 1 shows the inner 16 × 16 $arcsec^2$ of both the *K*-band image observed at UKIRT (left-hand panel) and the *I*-band image observed with *HST* (right-hand panel). Both clearly show the triple nucleus structure in the centre of IC 1695.

Using these images we have calculated the brightness of the three nuclei using three different methods. In the first of these we fitted a Gaussian to each of the nuclei, setting the background level to that of the underlying galaxy. In the second method, we fitted a polynomial to the underlying galaxy and subtracted the resulting fit. The total counts in each nucleus were then summed, using fixed apertures designed to encompass the light from only one of the nuclei. Elliptical apertures were used with semi-major axis, $a = 2.00$ arcsec for nucleus 1, $a = 1.00$ arcsec for nucleus 2 and $a = 1.73$ arcsec for nucleus 3. For the final method, an iteratively smoothed and nuclei-masked version of the original frame was subtracted from the latter, and the measurement was performed on the resulting image (containing only the nuclei). Again, the counts in each nuclei were summed within the same fixed apertures as in method 1. The three methods are complementary; they sample the galactic background in different regions, and hence their combined use allows us to estimate the uncertainty in the derived values contributed by the poorly constrained underlying galactic light. Each method gives a very similar result. We use the mean of the three estimates as our final measurement of the brightness of the nuclei. The error on this mean is taken as a standard error in the three measurements. The resulting brightnesses and colours of the nuclei are shown in Table 1. Photometric calibration of the *HST* image was performed using the measured WFPC2 zero-points reported in Holtzman et al. (1995). For the UFTI *K*-band image, UKIRT faint standards were observed throughout the night, in order to estimate the zero-point and extinction correction, using the standard star magnitudes reported in Hawarden et al. (2001).

Table 1. Magnitudes and colours of the three nuclei. See Fig. 1 for the numbering scheme used to identify the nuclei.

Nucleus	*K* band	*I* band	$I - K$
1	14.58 ± 0.05	16.32 ± 0.02	1.74 ± 0.05
2	15.77 ± 0.10	17.12 ± 0.03	1.35 ± 0.10
3	15.91 ± 0.13	17.48 ± 0.06	1.57 ± 0.14

Table 2 shows the separation of the nuclei. This is based upon a measured heliocentric recessional velocity of 14 505 km s^{-1} (de Vaucouleurs et al. 1991) for IC 1695 and an assumed Hubble

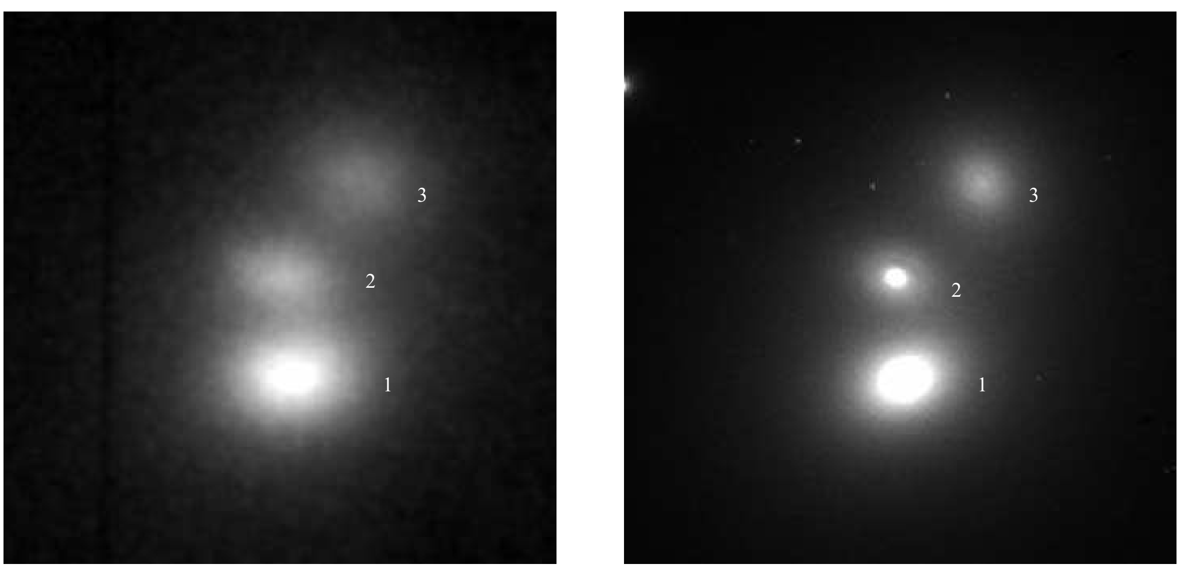

Figure 1. Left-hand panel: UKIRT/UFTI *K*-band image of the centre of IC 1695. Right-hand panel: *HST*/WFPC2 F814W *I*-band image of the centre of IC 1695. Both images show the triple nucleus in the centre of this galaxy.

Table 2. Distance between the nuclei. Column 1 reports the two nuclei for which the distance has been measured. Columns 2 and 3 have been calculated using the *HST*/WFPC2 F814W image. Columns 4 and 5 have been calculated using the UKIRT/UFTI *K*-band image.

Nuclei	*HST* F814W image		UKIRT *K*-band image	
	Distance (arcsec)	Distance (kpc)	Distance (arcsec)	Distance (kpc)
1–2	1.70 ± 0.05	1.60 ± 0.04	1.66 ± 0.09	1.56 ± 0.09
1–3	3.47 ± 0.05	3.25 ± 0.04	3.43 ± 0.09	3.22 ± 0.09
2–3	2.08 ± 0.05	1.90 ± 0.04	2.02 ± 0.09	1.89 ± 0.09

constant of $H_0 = 75$ km s^{-1} Mpc^{-1}. From this, the distance to IC 1695 is 193.4 Mpc. The precision with which one can measure the angular distances is assumed to be no better than 1 pixel. Both the *HST* image and the UKIRT image have been used for estimating the separations between the nuclei. The uncertainties are lower with the *HST* image, due to the higher resolution and the smaller pixel scale of WFPC2. The separations measured with the UKIRT image demonstrate that the measured distances are consistent with each other.

From the distances calculated between the nuclei it is possible for us to determine which of these nuclei had not been uncovered in earlier work. Hoessel & Schneider (1985) identified IC 1695 as having a double nucleus, and calculated a distance of ∼3.5 arcsec between them. It therefore seems that we have been able to determine that nucleus 1 and nucleus 2 are separate features for the first time, whereas earlier observations did not have the capabilities to resolve these two features.

Fig. 2 shows a colour image of the nuclei in IC 1695. This has been carefully aligned by sub-dividing each pixel in the UFTI array (using the MAGNIFY routine in IRAF) into a 2×2 square, resulting in approximately the same pixel scale as the PC on WFPC2. The original *K*-band image was convolved with the *HST* point spread function (psf) and the *HST* image was convolved with the psf of the UKIRT *K*-band image. The centre of each of the nuclei was calculated by fitting a Gaussian, and they were then aligned. The pixels were then binned up to the original UFTI pixel scale. The images have therefore been aligned to within 1 WFPC2 pixel.

The colour image shown in Fig. 2 suggests that the nuclei are bluer in colour than the typical colour of a BCG at $z = 0.048$, which is $I - K \simeq 1.9$. The colours of the nuclei (listed in Table 1) have been calculated pixel-by-pixel from Fig. 2. The bluer colour suggests that younger stars exist in this system than in a typical BCG. This could be due to a merger that may have taken place in the recent history of this galaxy. This would also account for the 'multiple-nuclei' structure. If the triple nucleus structure is the result of a merger between three galaxies, it would be expected that shortly after the merger, a burst of star formation was triggered, due to the large tidal forces involved (e.g. Cui et al. 2001). A possible result of such a phase in the recent history of a galaxy would be to make it appear bluer than other BCGs at the same redshift, due to the formation of a younger stellar population.

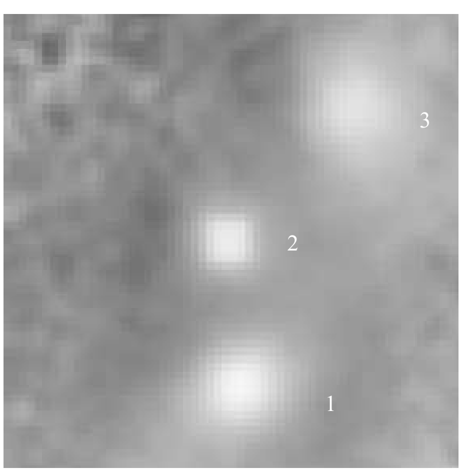

Figure 2. $I - K$ colour picture of the nuclei in IC 1695. Lighter areas are blue, darker areas are red.

We have also used *K*-band spectra of each nucleus to estimate its redshift, and therefore we can say with much more certainty that all three nuclei are part of the same system, rather than just projections of foreground or background galaxies. The spectra are shown in Fig. 3. They are devoid of emission lines, suggesting that this galaxy has no (or very little) gas. However, the redshift can be calculated from the 2.29-μm CO absorption feature. This has been modelled using stellar template spectra and calculating where this feature begins.

From the spectra, the redshift and recessional velocity of each nucleus has been calculated. As can be seen, the CO feature is redshifted to ∼2.4 μm in each nucleus, and this corresponds to a redshift of $z \simeq 0.048 \pm 0.001$. In this case the error has been calculated from the resolving power available with CGS4 and the 40 line mm^{-1} grating using a 0.6-arcsec slit. The S/N is also taken into account in the error. This redshift corresponds to a recessional velocity of $14\,400 \pm 300$ km s^{-1}. The error in the recessional velocity is similar to the typical velocity dispersion of an elliptical galaxy. It would therefore be difficult to achieve a better estimate of the recessional velocities. As a result, we can say that within the errors, the three nuclei all lie at the same redshift.

This result, combined with the fact that the nuclei are bluer than expected for a typical BCG, seems to suggest that the three nuclei are gravitationally bound within the same system.

4 DISCUSSION

As already discussed the chance projection of a background or foreground galaxy falling within a projected radius of 10 h^{-1} kpc ($H_0 = 100\,h$ km s^{-1} Mpc^{-1}) is 10 per cent (Tonry 1984; Hoessel & Schneider 1985). In other words, if IC 1695 actually has a double nucleus, then the chance of the third nucleus being a projection of a foreground or background galaxy is 10 per cent. However, if only one of these nuclei belongs to IC 1695, and both of the other nuclei are projections, then the chance of this is only 1 per cent, and therefore unlikely, unless one observes a sample containing hundreds of BCGs. The fact that clusters can be slightly elliptical, with their major axes being aligned with the major axes of giant elliptical galaxies (Porter, Schneider & Hoessel 1991) may slightly increase this chance, depending on the line of sight we have with respect to the major axis of the cluster. However, it still remains a slim chance.

Taking into account the blue colours of the nuclei, this suggests that all three galaxies would have actively been forming a young population of stars in their recent histories. This is unlikely for elliptical galaxies, unless they have been interacting in some way. Finally, the calculated redshifts for all three nuclei puts them at the same redshift, with an error consistent with the typical velocity dispersion of an elliptical galaxy. The simplest conclusion is that the three nuclei are gravitationally bound as parts of a common merged, or merging system.

Although this system may have recently been forming stars, this activity now seems to have ceased, and the galaxy spectra show no

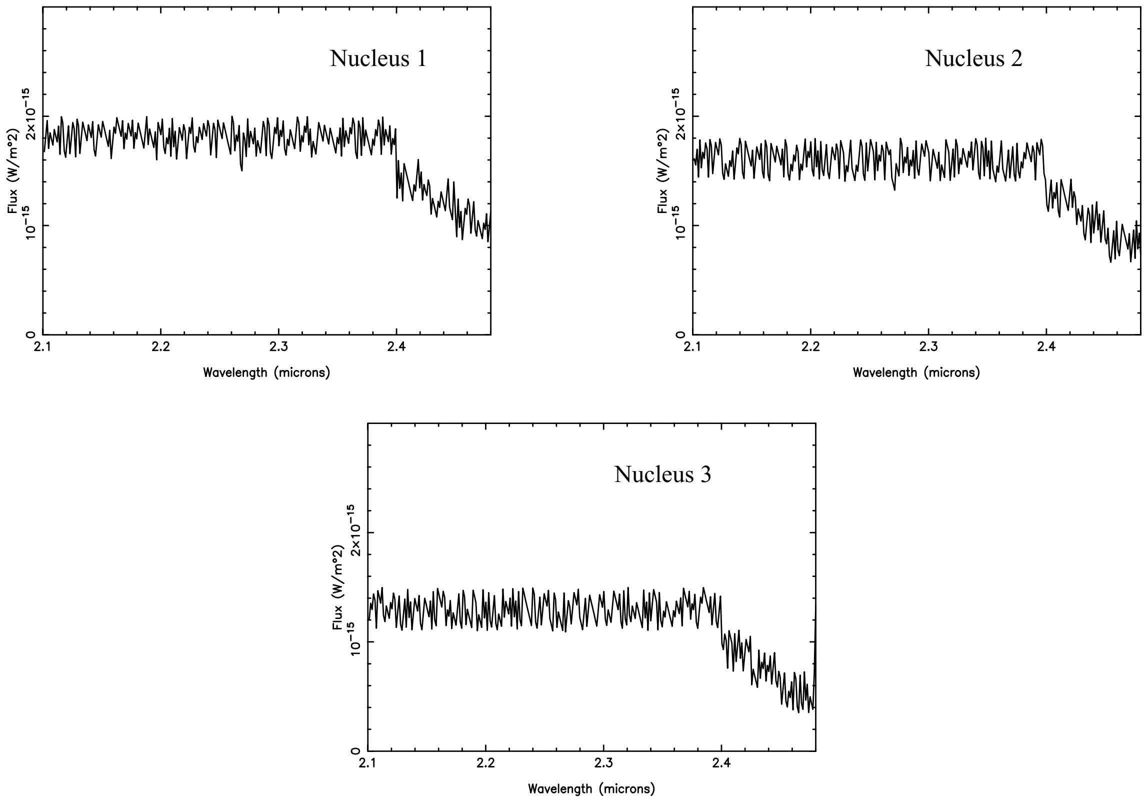

Figure 3. *K*-band spectra of the three nuclei, showing the 2.29-μm CO absorption feature redshift to ∼2.4 μm.

emission lines, due to very little (or no) gas being present to fuel further star formation. Optical spectra observed by Owen, Ledlow & Keel (1995) have also showed that there is no Hα emission from this galaxy, and this confirms the absence of any hydrogen gas. However, Owen et al. (1995) did find an absolute line luminosity of 3×10^{32} W for the [O II]3727 A line. At the distance of IC 1695, this corresponds to an apparent line strength of 1.20×10^{-16} W m^{-2}. This line is probably present, due to the fact that IC 1695 is a weak radio galaxy (Owen et al. 1995).

The time-scale on which the three components will merge depends on several factors. The density and velocity dispersion of a cluster determines the frequency at which mergers occur. The centres of clusters are the most dense areas and so the likelihood of finding a BCG with multiple nuclei is significant. In fact, Ryden, Lauer & Postman (1993) found that over 25 per cent of giant ellipticals in their sample had multiple nuclei. To find BCGs with multiple nuclei is therefore quite common, and one would assume that the time-scale on which the multiple nuclei merge is of the order of 10^9 yr (Murphy, Soifer & Matthews 2001). This time-scale has been calculated by studying the merging sequence of ULIRGs, via imaging spectroscopy of the Paα line. This data has shown that even after 10^9 yr, distinct nuclei can be still be seen in merging systems. Such a time-scale could explain why multiple nuclei are seen in so many central cluster galaxies.

Having said this it is important to note that the most conducive place for mergers is in the centres of intermediate density clusters and large groups, not necessarily the richest clusters (Böhringer, private communication). Density is important, but in the richest, most massive clusters the interaction velocities are so high that the galaxies can pass right through and by each other, but their relative velocity is high enough that they never become gravitationally bound to each other, and therefore a common, merged system cannot form.

5 CONCLUSIONS

We have observed a *K*-band image of the BCG in Abell 193 (IC 1695) in exceptional seeing conditions (FWHM ∼ 0.35 arcsec). This image has revealed a triple-nucleus structure, in a galaxy which was formerly thought to contain only two nuclei. This structure has been confirmed with the use of an *HST* archive WPC2 F814W *I*-band image. The $I - K$ colours revealed by the images suggest that the nuclei are bluer than expected from typical BCG colours at similar redshifts. This, combined with the spectra, which place the three nuclei at the same redshift of $z \simeq 0.048 \pm 0.001$, suggests that the three nuclei are indeed part of the same system.

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