Galaxy destruction and diffuse light in clusters

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ABSTRACT
Deep images of the Centaurus and Coma clusters reveal two spectacular arcs of diffuse light that stretch for over 100 kpc, yet are just a few kiloparsecs wide. At a surface brightness of $m_b \sim 27–28$ mag arcsec$^{-2}$, the Centaurus arc is the most striking example known of structure in the diffuse light component of a rich galaxy cluster. We use numerical simulations to show that the Centaurus feature can be reproduced by the tidal debris of a spiral galaxy that has been tidally disrupted by the gravitational potential of NGC 4709. The surface brightness and narrow dimensions of the diffuse light suggest that the disc was corotating with its orbital path past pericentre. Features this prominent in clusters will be relatively rare, although at fainter surface brightness levels the diffuse light will reveal a wealth of structure. Deeper imaging surveys may be able to trace this feature for several times its presently observed extent, and somewhere along the tidal debris, a fraction of the original stellar component of the disc will remain bound, but transformed into a faint spheroidal galaxy. It should be possible to confirm the galactic origin of the Centaurus arc by observing planetary nebulae along its length with redshifts close to that of NGC 4709.

Key words: methods: numerical – galaxies: clusters: general – galaxies: clusters: individual: Centaurus – galaxies: evolution – galaxies: formation – galaxies: interactions.

1 INTRODUCTION
Detecting diffuse light in clusters has an enigmatic history spanning several decades (de Vaucouleurs 1960; Thuan & Kormendy 1977; Uson, Boughn & Kuhn 1991; Frei & Gunn 1994; Vilchez-Gómez, Palló & Sanahuja 1994; Bernstein et al. 1995; Tyson & Fischer 1995). Using either charge-coupled devices (CCDs) or photographic imaging, these observations have been plagued by background subtraction, stray light within the telescope and optics, and atmospheric scattering. This has made a quantitative analysis difficult: the total amount of diffuse light, its colour, or its radial distribution have not yet been accurately measured. These techniques have led to claims that as much as 70 per cent of the light attached to galaxies may lie in a diffuse component. More recently, individual planetary nebulae have been detected, in between cluster galaxies and with redshifts and velocities that place them inside the cluster potential (Arnaboldi et al. 1996; Theuns & Warren 1996; Feldmeier, Ciardullo & Jacoby 1997). Hubble Space Telescope (HST) deep images of the Virgo cluster have also revealed a large population of freely orbiting, red giant stars (Ferguson, Tanvir & von Hippel 1998). These studies also indicate that large quantities of diffuse light exist in clusters.

Intragalactic stars must have formed within galaxies and have been subsequently ripped out by gravitational tidal forces. Mergers and slow tidal interactions between galaxies are a well studied phenomenon that can produce dramatic tidal tails of stellar debris (cf. Toomre 1964; Barnes & Hernquist 1992 and references therein). Analysis of dark matter haloes within a galaxy cluster that formed hierarchically has demonstrated that mergers are very rare within rich virialized environments (Ghigna et al. 1998). However, the impulsive and resonant tidal shocks from rapid fly-by encounters between galaxies can also create tidal debris. The cumulative effect of these encounters can cause a dramatic morphological transition between Sc–Sd spirals to dwarf ellipticals/ spheroidals (Moore et al. 1996; Rakos, Odell & Schombert 1997), whereas low surface brightness galaxies, with lower central densities, can be completely disrupted, leading to a possible origin of the diffuse intracluster light (Moore et al. 1998b). This process has been named ‘galaxy harassment’, and extends previous work on slow interactions between galaxies into the impulsive tidal processes that operate in galaxy clusters (Merritt 1985; Valluri 1993; Henriksen & Byrd 1996; Moore, Lake & Katz 1998a; Dubinski 1998).

In the absence of further perturbations, stars that are tidally
removed from galaxies will orbit in narrow streams that trace the orbital path of the galaxy. In a cluster, the star streams will be subsequently heated and mixed on a time-scale of a few crossing times, i.e. several billion years. We might therefore expect to find prominent features in the intracluster light component from recently disrupted galaxies that have accreted into clusters a few billion years ago. However, with only a couple of documented examples, why are prominent features as bright as these so rare?

The properties of the diffuse light, including its quantity, radial distribution, clumpiness and colour, are of great interest for many reasons. As well as constraining the importance of gravitational interactions as a mechanism for morphological transformation, we have the possibility of using thousands of freely orbiting stars for studying the cluster potential. Understanding the orbital biases of stripped stars and their subsequent evolution within a clumpy structure is an attempt to reproduce the properties of the Centaurus arc, using numerical simulations to follow the disruption of galaxies within a cluster potential. We summarize these results in Section 4.

2 THE IMAGES

The Centaurus arc was originally discovered by applying a photographic amplification technique (Malin 1978) to three plates taken in 1974 by Malcolm Smith at the f/2.66 prime focus of the 4-m telescope of the Cerro Tololo Inter-American Observatory (CTIO). The photographic emulsion was Eastman Kodak type IIIa-J, hypersensitized by baking in nitrogen before use. Photographic amplification and positive derivatives from these plates were combined into one image (Malin 1981) to improve the image quality and to minimize processing non-uniformities. The arc was clearly visible on each of the three copies, and its reality was later confirmed by photographic amplification of IIIa-J plates taken with the 3.9-m Anglo-Australian Telescope (AAT) and the 1.2-m UK Schmidt telescope.

More recent CCD observations reveal that, if this structure lies in the cluster, it is \( \sim 120 \, h^{-1} \text{kpc} \) (\( \sim 12 \text{arcmin} \)) long and only 1–2 \( h^{-1} \text{kpc} \) (\( \sim 10–15 \text{arcsec} \)) wide (throughout this paper \( H_0 = 100 \, \text{h} \, \text{Mpc} \, \text{km} \, \text{s}^{-1} \cdot \text{M}_{\odot}^{-1} \)). The arc has very low surface brightness (\( \mu_B ^{\text{g}} \approx 27.8 \, \text{mag} \, \text{arcsec}^{-2} \)), is red in colour and points towards the active elliptical galaxy NGC 4696. The arc’s colour strongly suggests that it is made of stars, so its narrowness is remarkable. The arc is not perfectly straight and has a small curvature along its length.

The top half of Fig. 1 shows a negative print of part of the photographically amplified, combined images of the CTIO plates. The arc is the linear feature that extends from the lower left corner (south-east) towards the nucleus of NGC 4696. The lower image shows the same part of the sky on a single unamplified plate.

The photographs (and CCD frames) show the arc to be diffuse and seemingly devoid of fine structure at the arcsec level. While there are many faint stars and galaxies in the field, there is no apparent enhancement of point-like or diffuse objects along its length (the point-like source near the centre of the arc is a star). The arc first becomes visible near a small, edge-on S0 galaxy, ESO 322-G102, at a projected distance of about \( 80 \, h^{-1} \text{kpc} \) from NCG 4696; the truncation of the arc at this point may be a line-of-sight coincidence, since there is no evidence of any interaction between the arc and ESO 322-G102. Subtraction of the extended light profile of NGC 4696 may reveal the arc on the opposite side of the S0 galaxy.

Spectroscopy of the arc would be extremely difficult in view of its very low surface brightness. However, narrow-band CCD images of the brightest regions were obtained, making it possible to compare the colours of the arc with aged stellar populations. CCD pictures were taken in \( B, R \) and \( I \) bands with an RCA 350 \( \times \) 512 chip at the f/3.3 prime focus of the AAT under photometric conditions on the night of 1990 June 21/22. The CCD scale was 0.49 arcsec pixel\(^{-1}\), and the seeing 2–3 arcsec. Two sets of overlapping exposures were taken, with total exposure times of 90 min in \( B \), 40 min in \( R \) and 20 min in \( I \). Flat fields and bias frames were taken on the same night.

Table 1 lists the surface brightness and colours of the arc as measured from the overlap region of the CCD frames. In each case, the mean surface brightness in three regions along the arc was measured, each roughly 5 \( \times \) 5 arcsec\(^2\) and free of obvious foreground stars, and six ‘sky’ regions of similar area straddling the arc and just outside it. The errors quoted in Table 1 are \( 1\sigma \) errors on the mean of the three sky-subtracted arc measurements in each filter.

The CCD measurements confirm that the arc is extremely diffuse and very faint, reaching no more than 0.7 per cent of the brightness of the night sky. Further out, the arc is even fainter, and we estimate that the faintest parts of the structure revealed by the photographic plates are only 0.1 per cent of the night sky brightness.

The same techniques have also been applied to photographic images of the central regions of the Coma cluster (Abell 1656). These have revealed a feature in the diffuse light, close to NGC 4874, that stretches east–west for at least 5 arcmin, \( \sim 150 \, h^{-1} \text{kpc} \) (Fig. 2). It is curved slightly concave to NGC 4874 in a manner very similar to the curve in the Centaurus cluster feature where it appears closest to NGC 4709. The image was made by combining photographically amplified derivatives from three UK Schmidt plates. Two of the plates (J9946 and J10027) were deep IIIa-J (395–550 nm) exposures while one was plate OR9945 covering the range 590–700 nm. The linear feature is visible individually on all of the plates, but is much less obvious on the red-light plate. Given the large airmass through which the exposures were necessarily made and the smaller number of plates, this suggests that the surface brightness of the Coma arc is higher than that in the Centaurus cluster. The large airmass has also contributed to the relatively poor seeing in these plates, which is probably why we are unable to confirm the Trentham & Mobasher (1998) feature.
The Coma arc is neither as narrow nor as well defined as that in the Centaurus cluster, and two resolved galaxies appear to be embedded in the brightest part of it. Given the large number of galaxies in the field, this could be a line-of-sight coincidence, or one of these could be the remnant nucleus of a disrupted galaxy. We note that this feature in Coma was reported independently by Gregg & West (1998). In the absence of CCD photometry of the Coma arc, and its poorer resolution because of its distance, we shall focus our attention on the origin of the Centaurus arc.

### Table 1. Surface brightness and colours of the arc and sky.

|          | Surface brightness (mag arcsec⁻²) | Colour (mag)          |
|----------|----------------------------------|-----------------------|
| Arc      | $\mu_B = 27.81 \pm 0.08$         | $B - R = +1.72 \pm 0.13$ |
|          | $\mu_R = 26.09 \pm 0.05$         | $R - I = +0.35 \pm 0.22$ |
|          | $\mu_I = 25.74 \pm 0.17$         |                       |
| Sky (I frame in twilight) | $\mu_B = 22.52$ |                       |
|          | $\mu_R = 20.76$                  |                       |
|          | $\mu_I = 18.78$                  |                       |

The Coma arc is neither as narrow nor as well defined as that in the Centaurus cluster, and two resolved galaxies appear to be embedded in the brightest part of it. Given the large number of galaxies in the field, this could be a line-of-sight coincidence, or one of these could be the remnant nucleus of a disrupted galaxy.

2.1 Possible origins

The Centaurus arc is unlikely to be foreground reflection nebulosity in our own Galaxy. Malin has used his photographic amplifications technique on many fields containing Galactic nebulosity, and notes that the Centaurus feature (at Galactic latitude 22°) is morphologically quite different. In particular, it lacks the high-frequency ‘crumpling’ characteristic of Galactic cirrus and reflection nebulosity. Also, the arc is almost straight (it deviates from a straight line by at most 3–4 arcsec in the 100-arcsec length covered by the CCD frames) and points at the...
nucleus of NGC 4696, the brightest galaxy in the Centaurus cluster.

The region of the arc observed with the CCD has colours consistent with those of K0 stars in the \((B - R)\) versus \((R - I)\) two-colour diagram (Fig. 3; Cousins 1981). If the arc were dominated by optical synchrotron radiation, it would be bluer than this, with \(B - R\) around 0.7–1.2 as typically seen in BL Lac objects (Moles et al. 1985) and the M87 jet (Tarenghi 1981).

**Figure 2.** A high-contrast image of the core of the Coma galaxy cluster with NGC 4874 at the upper right. At the distance of Coma, 1 arcmin is approximately \(30 h^{-1}\) kpc.
Whilst the arc might be composed of ionized gas, with most of its light coming from O\textsuperscript{2+} and H\textsuperscript{+} ions, very unusual line ratios would be needed to produce the observed colours and it would be difficult to account for the I-band emission. Furthermore, it is hard to imagine a long-lived ionizing source that could operate over such a large distance. If light from the arc originated from emission lines, we would also need to account for the collimation of the ionized gas, or the ionizing beam, or both. We therefore conclude that the arc is probably composed of stars with a mean spectral class of around K0.

Could the feature be a gravitational arc from a background galaxy that has been lensed by the combined potential of NGC 4696 and 4709? In order to produce a gravitationally lensed image this straight, the potential has to be complex, such as would occur in between the combined potential of the two central cDs. Furthermore, a lensed image this close to the massive potential of NGC 4709 would produce a much shorter image. Thus, if the mass distribution traces the light distribution to a reasonable extent, then its position and morphology rule out gravitational lensing.

The dimensions of the object rule out a diffuse galaxy that happens to lie along the line of sight – the axial ratios are about 60:1. If the Centaurus arc is stellar and lies in the cluster, then either the stars formed in situ, or they have been removed from one of the cluster galaxies; since no mechanism is known for the former, we shall concentrate on the latter. In either case, the key challenge for any successful model for its origin is to reproduce both the length and narrowness of the feature.

We can estimate the mass of the stars in the arc from its integrated luminosity. Combining measurements of its area and mean surface brightness gives an estimated total B magnitude of 18.4 ± 0.5 for the integrated light. At the distance of the Centaurus cluster (taken here as 26.8 h\textsuperscript{-1} Mpc), this is roughly 4 h\textsuperscript{-2} x 10\textsuperscript{7} L\textsubscript{\odot}, corresponding to 8 h\textsuperscript{-2} x 10\textsuperscript{5} M\textsubscript{\odot} if we assume a mass-to-light ratio of M/L\textsubscript{B} = 2.

The remainder of this paper will be devoted to investigating the possibility that the Centaurus arc consists of stars that have been tidally stripped from a cluster galaxy. Since the total stellar mass of the arc is just a few per cent of the stellar mass of an L\textsubscript{\odot} galaxy, we have two possibilities for the progenitor galaxy. It may have originated from a single dwarf galaxy that has been completely disrupted and all the original stars form the 100 kpc streak of light. Alternatively, the observed feature may represent part of the tidal debris that has been torn from a more luminous galaxy. In the latter case, the bulk of the tidal debris may extend beyond the current image and may be detectable at lower surface brightness levels.

3 TIDES AND TAILS; NUMERICAL SIMULATIONS

We shall use numerical simulations to investigate the possibility that the Centaurus arc is tidal debris from a gravitational interaction between a galaxy and one of the cD galaxies NGC 4696 or 4709. Although there is a wide parameter space to explore, in both morphology and orbits, it is clear that spheroidal galaxies (either dwarf elliptical/dSph or giant ellipticals) are unlikely candidates. Ellipticals are too centrally concentrated to lose a great deal of stars, and their tidal debris will not occupy such a narrow region in phase space.

The position of the Centaurus arc next to the cluster centre suggests that the potential of one of the massive central cD galaxies was responsible for the disruption. However, we cannot rule out the possibility that the encounter took place further from the cluster centre and we are observing the debris passing pericentre. Rather than treat the full cluster potential and its substructure, we shall model the cD galaxy as a single truncated isothermal dark matter halo with a moderate core radius of 50 kpc and mean velocity dispersion of ~900 km s\textsuperscript{-1}.

We will study galaxies with global properties that resemble observed spheroids and discs of varying surface brightness and luminosities (cf. Moore et al. 1998b and Fig. 4). Equilibrium ‘N-body’ galaxy models are constructed using the techniques of Hernquist & Katz (1989). To evolve the galaxies in orbit through the cluster potential, we use the parallel treecode PKDGRAV (Stadel et al., in preparation). When we simulate the galaxies in isolation, they are stable and remain in equilibrium. We explore a wide range of orbits that allow us to vary the strength of the impulsive shock and then compare the properties of the tidal debris with the Centaurus data. Following the galaxies for several gigayears, we

Figure 4. The rotation curves \(\propto \sqrt{M/r}\) of our model spiral galaxies with (a) high surface brightness (HSB) and (b) low surface brightness (LSB). The contributions to the rotation curve from the different components of the spiral galaxies are indicated. Note that these models are constructed to represent observed galactic systems – both have the same peak rotational velocity and lie on the same part of the Tully–Fisher relation, yet have different central mass distributions.
conclude that orbits with apocentric distance \( \sim 1000 \) kpc and pericentric distance of \( \sim 150 \) kpc produce the longest and thinnest tidal streams. This orbit is close to the typical orbit of 'haloes within haloes' for a hierarchical Universe measure by Ghigna et al. (1998).

For the spheroidal models, long streams of debris are obtained, but they are over 3 mag too faint to explain the Centaurus arc. Even after several passages past pericentre, most of the material remains bound to the galaxies. We would require the entire system to be disrupted into a single smooth stream of length \( \sim 100 \) kpc in order to explain the Centaurus feature. We were unable to achieve this.

The orbits of the spiral galaxies have an extra degree of freedom, namely the orientation of the disc as the galaxy moves past pericentre. We consider the extreme cases of a disc that is either counter-rotating or corotating with respect to the orbital direction. Fig. 5 shows the evolution of one of the low surface brightness spirals in a counter-rotating orbit.

The first tidal shock occurs after 1.0 Gyr, yet after 1.5 Gyr the disc does not appear to be too disturbed. After 2.75 Gyr (almost 2.0 Gyr after the encounter) the response to the perturbation is clearly apparent and the stripped stars surround the central stellar remnant. Continued heating after several more pericentric encounters almost completely unbinds the system, although the tidal debris never forms narrow features in phase space.

We now change the direction of the orbit through the cluster.

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**Figure 5.** The evolution of the LSB galaxy on a counter-rotating orbit. The left-hand panels show the entire orbit centred on the cluster potential in a \( 3000 \times 3000 \) kpc\(^2\) box. The two right-hand panels measure \( 100 \times 100 \) kpc\(^2\) and correspond to close-up views of the galaxy: face on (centre panels) and edge-on (right panels). Note that, for clarity, we plot just one-fifth of the star particles projected on to the orbital plane, and the cluster particles are not plotted to avoid confusion.

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potential such that the disc is corotating with the galaxy's direction past pericentre. After just 0.5 Gyr, the morphology of the galaxy shown in Fig. 6 has been dramatically altered. Already, most of the disc structure has been destroyed, and the stellar distribution has been significantly heated. However, the most significant change occurs in the appearance of the tidal debris. At 1.0 Gyr after the first encounter the tidal debris begins to form long thin tidal tails of stars that have been symmetrically torn from the disc and trace the orbital path of the galaxy. In this case, 90 per cent of the stars have been stripped, although the remaining stars remain bound in a spheroidal configuration with an exponential surface brightness distribution.

The tidal debris from both HSB and LSB galaxies can create long ($\geq 200$ kpc) and thin ($\leq 8$ kpc) diffuse arc-like features. Fig. 6 shows that the debris has the narrowest dimension and would be most luminous as it is passing pericentre. At this point, the orbits of the stars bunch up because they are moving through the deepest part of the potential. It is this section of the tidal debris that we associate with the Centaurus arc, which also lies close to the centre of the cluster potential. We illustrate this in Fig. 7.

Because the HSB galaxies are more centrally concentrated, they lose less material and the resulting tidal features are not as prominent. Can we distinguish between these two possibilities? At time $t = 2.75$ Gyr we extract a 100-kpc length of the stellar debris that is just approaching pericentre and then project the data to measure its surface brightness. The central surface brightness of the inner contour of the LSB galaxy is $m_B = 27.8$ arcsec$^{-2}$, while for the HSB it is $m_B = 28.3$ arcsec$^{-2}$. For this conversion we have assumed a mass-to-light ratio of $M/L_B = 2$. Although the difference is small, it suggests that LSB galaxies produce brighter

\[ \text{Figure 6.} \text{ As Fig. 5, except that the LSB galaxy has been placed on a corotating orbit.} \]
features, although a great deal of uncertainty arises from the assumed mass-to-light ratios.

A larger fraction of stars were stripped from discs that are corotating with their orbit, and the stripped stars formed long narrow streams that resembled the Centaurus arc. We can understand why this happens by considering the relevant dynamical time-scales. The impulsive shock occurs on a time-scale $t_0 = 2r_p/v_i \, \text{Gyr}$, where the impact velocity of the galaxy is $v_i = 3000 \, \text{km s}^{-1}$ as it moves past pericentre $r_p = 120 \, \text{kpc}$. We can compare this time-scale with the time it takes for the disc stars to make half a revolution within the core radius of the galaxy, $t_{\text{core}}$, 

$t_{\text{core}} = \frac{\pi r_{\text{core}}}{v_c}$, where $v_c = 200 \, \text{km s}^{-1}$. For the particular galaxy and orbit simulated here, $t_{\text{core}} \sim t_0 = 0.1 \, \text{Gyr}$. If the disc is corotating, then the encounter occurs closer to a resonance and more energy is imparted to the disc stars, which can subsequently spread further through the cluster potential.

Our simulations showed that the orbits of the stripped stars move closer together as they move through pericentre. This creates the appearance of a ‘standing wave’ near the cluster centre, where the surface brightness of the debris is significantly enhanced. The orbits bunch together near pericentre because the gradient in the cluster potential is larger in the centre. We can make a rough quantitative estimate of the enhancement in surface brightness as follows: Consider two stars in circular orbits near the cluster centre at distances $r_{a1}$ and $r_{a2}$, separated by a small radial distance $\Delta r_a$. What happens to the separation of the particles as we move the orbits further out into the cluster, but preserve the small energy difference between the two particles? Now the particles orbit at distances $r_{p1}$ and $r_{p2}$, this time separated by $\Delta r_p$.

The total energy of each orbit ($E_i$) is conserved and equal to $E_i = K_i + \Phi_i$, where $K_i$ is the kinetic energy term for each orbit and $\Phi_i = 2\sigma^2 \ln(r_i/R)$ its corresponding potential energy. [Note that we have use a truncated isothermal spherical potential, where $\sigma$ is the constant velocity dispersion and $R$ is the truncation radius.] Because we are dealing with an isothermal potential, all circular orbits have the same kinetic energy, and therefore the difference in total energy for each pair of orbits is given by:

$|\Delta E_A| = |\Phi_A| = |2\sigma^2 \ln(r_{a2}/r_{a1})|$, 

$|\Delta E_B| = |\Phi_B| = |2\sigma^2 \ln(r_{p2}/r_{p1})|$. 

If the energy difference of both orbits is the same then

$|\Delta E_A| = |\Delta E_B|$, 

$\ln(r_{a2}/r_{a1}) = \ln(r_{p2}/r_{p1})$, 

which leads to 

$\Delta r_a = (r_{a1}/r_{a2}) \Delta r_p$.

Thus for a given energy difference, orbits tend to get closer together as they move towards the central regions of the potential. For an orbit with apo:peri of 10:1, the enhancement of the surface

Figure 7. An illustration of the part of the tidal debris from the LSB disc galaxy that we associate with the observed arc of light in the Centaurus cluster. The star particles from the LSB galaxy are plotted 2.75 Gyr after the galaxy enters the cluster, roughly 1.5 Gyr after the first pericentric passage. These data have been inclined at 30° to the line of sight. At this time, the stellar remnant is approaching pericentre for the second time. The small box centred on the tidal debris shows the part of the stream that we may be observing in the deep image of the Centaurus cluster shown above the tidal debris. The cross in the small box shows the centre of the cluster potential.

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brightness of the tidal stream will be roughly a factor of 10 at pericentre.

Further support for stellar debris of a galactic origin can be found by considering the colours of the Centaurus arc. In Table 2 we give typical colour differences for galaxies of different morphologies across the Hubble diagram (Frei & Gunn 1994; de Blok, van der Hulst & Bothun 1995). Once the stars are removed from the galaxy, star formation will be abruptly halted and the stars will fade in a predictable manner. Fig. 8 shows how the colour indices fade with time for a given stellar population with known metallicity and initial mass function (Bruzual & Charlot 1993, in preparation).

The tidal tails match the appearance of the Centaurus arc ~1 Gyr after being stripped from the model galaxies, i.e. the time since the first passage past pericentre. After 1 Gyr, the amount of fading will be 0.77 and 0.17 for $B - R$ and $R - I$, respectively. We now reconsider the observed values for the arc (see Table 1). We add a further correction for Galactic dust reddening using the data of Burstein & Heiles (1982) and Schlegel, Finkbeiner & Davis (1998). This brings the values of the colours to:

$$B - R = 1.52 \pm 0.14,$$
$$R - I = 0.27 \pm 0.23.$$

If we take into account the amount of fading over 1 Gyr, then the initial stellar colours of the stars in the arc would have been $B - R = 0.75$ and $R - I = 0.10$. These colours, within the uncertainties, are consistent with late-type spirals and LSB disc galaxies, providing further support for our model.

### 4 CONCLUSIONS

Deep photographic and CCD observations of the Centaurus cluster revealed a spectacular arc of diffuse light. This feature is remarkable given its length and narrowness, ~12 arc-min (≈120 h\(^{-1}\) kpc) long and ~10 arcsec (≈2 h\(^{-1}\) kpc) wide. The arc is diffuse with no apparent structure and its colours indicate that it is made of stars. The estimated total mass from its integrated luminosity is $8 h^{-2} \times 10^7 M_\odot$ and its surface brightness (in mag arcsec\(^{-2}\)) is $\mu_B = 27.8$, $\mu_B = 26.1$, in the $R$ band, and $\mu_B = 25.7$, in the $I$ band. Several possible scenarios for its origin, including foreground reflection nebulae, gravitational lensing or a radio jet, are rejected in favour of a gravitational tidal interaction that created an arc of stellar debris. A second feature with similar morphology is also revealed within the central region of the Coma cluster.

We used numerical simulations to investigate the response of galaxies of different morphologies to tidal shocks as they pass pericentre in a cluster potential. The only scenario that gave rise to tidal debris with the same characteristics as the Centaurus arc was a luminous spiral galaxy with a disc corotating with its passage past pericentre. This encounter geometry imparts the maximum energy to the disc stars, allowing them to stream away and form long thin tidal tails of stellar debris that trace the orbital path of the galaxy. Only a small fraction of the tidal debris constitutes the Centaurus feature, which is prominent at its current pericentric position where the orbits move closer together.

One could potentially confirm the galactic origin of the Centaurus arc. By taking images along its length using different filters (e.g. O\(\text{III}\) and H\(\alpha\)) such as discussed in Feldmeier et al. (1997), one would expect to find an overabundance of planetary nebulae at similar redshifts to NGC 4709, thus confirming the stellar nature and formation mechanism. Deeper images of these features should allow them to be traced to larger extents. Somewhere along the tidal tails lies the remnant spheroidal galaxy surrounded by a cloud of diffuse light that closely resembles the feature reported by Trentham & Mobasher (1998).

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