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Do galaxy mergers form elliptical galaxies? A comparison of kinematic and photometric properties

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ABSTRACT

We present near-infrared *K*-band imaging and spectroscopy of a sample of galaxy mergers, which we use to derive light profile indices, absolute magnitudes and central velocity dispersions. We find that the light distributions of mergers more nearly resemble those of ellipticals than those of bulges, but that the mergers lie well away from the Fundamental Plane defined by the ellipticals. We interpret this as being due to enhancement of the *K*-band surface brightness of the mergers by a significant population of supergiant stars, and independent evidence for such a population is inferred from measurements of the depth of the 2.3-μm CO absorption feature.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: fundamental parameters – galaxies: interactions – galaxies: stellar content – galaxies: structure.

1 INTRODUCTION

The fate of mergers of gas-rich galaxies is an enduring question, which has attracted significant observational and theoretical interest. Such mergers must happen, and are probably common in at least some galaxy environments; but opinion is sharply divided on the end-product of this process. This is a possible mechanism for producing elliptical galaxies, but it has also been argued that diffuse, dynamically cold disc-dominated systems cannot become highly centrally concentrated elliptical galaxies, and that the end-product of a disc–disc merger is likely to be something much more flimsy and diffuse (Ostriker 1980). Given this uncertainty, it is clearly of interest to study the properties of systems that are generally acknowledged as merger remnants, to determine their likely fates. This is the purpose of the present paper, with the ultimate aim of this programme being to investigate a possible evolutionary sequence between mergers and elliptical galaxies.

There are problems with using optical imaging and spectroscopy to study the dynamics of mergers. Mergers are extremely dusty systems, with visual extinctions of ~ 10 mag towards their nuclei in the early stages of the merging process, and the dust tends to be in a very irregular distribution. This causes great uncertainties in the interpretation of optical measurements of these systems, since the optical emission must come from an irregular outer shell of the galaxy which represents the most disturbed and unrelaxed component. This is particularly unfortunate for studies of the progression of the relaxation process in mergers, since relaxation will first occur in the central region where the characteristic time-scales are shortest. These regions can in principle be observed in H I 21-cm emission, which is unaffected by the extinction problem, but many galaxies are known to have central deficiencies of atomic gas, and in very disturbed systems it is far from certain that the dynamics of the gas component bear any relation to the stellar component in which we are interested here.

The near-infrared thus provides the best techniques for measuring directly the kinematics of the stellar component in the presence of extinction. *K*-band (2.2 μm) light is affected by extinction an order of magnitude less than blue light, and thus can probe deep into the centres of these galaxies. This light is dominated by the old stellar population, at least in normal galaxies. Rix & Rieke (1993) find that, in the discs of star-forming galaxies, there is a significant contribution from red supergiants, of the order of 15–25 per cent of the *K*-band light, but this is very much less than the contribution of young stars to the optical emission in such systems. We consider the effects of supergiant emission in the *K* band for an extreme starburst system later in the paper. It is fortunate also that the *K* band contains the strong CO absorption feature which is well suited to the measurement of velocity dispersions of galaxies (Doyon et al. 1994b; Lester & Gaffney 1994; Gaffney, Lester & Doppmann 1995). Since this is a photospheric absorption, it traces directly the kinematics of the stellar population. Thus, by combining *K*-band photometry with

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CO spectroscopy, it is possible to study the structure and kinematics of the stellar population in the central regions of merging galaxies. This is the aim of the present work.

2 PREVIOUS WORK

Many authors have contributed to the literature on this subject. Toomre & Toomre (1972) made the cautious suggestion that dynamical friction and consequent merging of pairs of disc galaxies 'seems like a scenario for nothing less than the delayed formation of some elliptical galaxies – or at least of major stellar halos from otherwise gas-rich disks'. Many numerical simulations of the merging process have been performed (e.g. Toomre & Toomre 1972; White 1979; Farouki & Shapiro 1982; Barnes 1988), and have almost unanimously concluded that the $R^{1/4}$ profile typical of luminous elliptical galaxies is the natural outcome of the merging process. This has received some observational support, with both optical (Schweizer 1982) and near-infrared (Wright et al. 1990; Stanford & Bushouse 1991) imaging showing the apparent emergence of such profiles in on-going mergers. There are some problems with the merger/elliptical scenario, however. The phase-space argument of Ostriker (1980) remains unresolved, although the discovery of strong central concentrations of molecular gas in mergers (Sanders et al. 1986) and subsequent nuclear starbursts (Joseph & Wright 1985) may contribute the extra stellar density needed to resolve this discrepancy. The apparent deficit of globular clusters in spirals relative to ellipticals also remains problematic, with the suggestion that globulars may be made during the merging process (Schweizer 1986) now being seriously challenged (Whitmore & Schweizer 1995). It is also possible that the $R^{1/4}$ profiles in some or all of the mergers are due to pre-existing bulge components, and may not be indicative of the light profile of the entire system when relaxation has been completed.

While this paper was in preparation, a very similar study was published by Shier & Fischer (1998). They also used the CO absorption feature to determine central velocity dispersions, in their case for a sample of 10 galaxy mergers. In general, their conclusions are very similar to ours, and the results will be compared throughout the present paper.

3 GALAXY SAMPLE

Galaxies were chosen on the basis of a variety of visual morphological criteria, which are generally accepted as being indicative of disc galaxy mergers. The most important of these is the presence of extended, narrow tails which are found in *N*-body simulations to be a general feature of galaxy mergers, and are caused by the strong tidal field generated during the merging process. The central regions of the mergers are visually chaotic, due in large part to the disrupted dust lanes of the pre-merger spirals. Redshifts were restricted to $< 15\,000\,\mathrm{km\,s^{-1}}$ to ensure that the CO absorption edge, at a rest wavelength of 2.293 μm, remained well within the *K* atmospheric window.

4 OBSERVATIONS

All observations presented here were made with the 3.8-m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. *K*-band imaging was obtained on the three nights of 1990 April 30–May 2, using the near-infrared camera IRCAM, which employed a 62×58 pixel InSb array. The 60-mm focal length camera was used, giving a pixel scale of 1.24 arcsec. All the observations were made in the standard *K* filter. Exposure times were typically 10–15 s on-chip before reading, to give sky-background-dominated noise, co-added to give 30–40 min total exposure per galaxy. Equal time was spent on nearby sky positions to build up sky flats. Telescope pointings were jittered around the mean position to increase the area observed around galaxies, and to enable the sky flats to be median-filtered, thus minimizing the effect of foreground stars. Seeing was typically ~ 1.5 arcsec, but was difficult to estimate exactly because of the large pixel scale used.

High-resolution spectroscopy at 2.3 μm was obtained using the spectrometer CGS4 on UKIRT on the three nights of 1994 June 6–8. At that time, CGS4 used a 62×58 pixel InSb array. We used the high-resolution echelle grating and the long focal length camera with a 2 pixel wide slit, giving a FWHM spectral resolution equivalent to $16\,\mathrm{km\,s^{-1}}$ and a spectral range of 0.01 μm. Given the small spectral range, two grating positions were used for each galaxy, giving a total spectral coverage of 2.285–2.305 μm in the rest frame of the galaxy. For each galaxy, between 15 and 20 integrations each with exposure times of ~ 180 s were taken. The telescope was nodded so as to slide the target galaxy up and down the slit between integrations to facilitate sky subtraction. Observations were also made of A stars to enable atmospheric absorption features to be divided out, and BS 4737, a K1 III star, was observed to provide a template of the CO absorption profile.

5 DATA REDUCTION

5.1 Imaging

Imaging data reduction was standard, using the KAPPA and FIGARO packages. All frames were bias- and dark-subtracted, using dark frames with the same on-chip exposures as the science frames and scaled to the same number of co-adds. Flat-fielding was performed using median sky flats taken in blank sky areas adjacent to the galaxy concerned, and with the same exposure time as the galaxy. Attempts to improve the signal-to-noise ratio of the flats by including frames taken over a longer period of time yielded lower quality final images, probably owing to changes in the effective flat-field pattern as a function of changing sky colour. Each galaxy was observed in at least four 'jittered' pointings, and these were combined into mosaics after flat-fielding and sky subtraction of the individual sub-arrays. Photometric calibration was taken from images of the standard stars GL 406, HD 77281, HD 84800, HD 105601, HD 106965, HD 136754, HD 161903 and HD 162208, which showed an overall photometric scatter of ± 0.04 mag, when the zero-points for all three nights were combined. The galaxy images were calibrated using the zero-point from the standard nearest in time and airmass, and differential airmass corrections were very small, typically 0.01 or 0.02 mag. The derived galaxy light profiles for NGC 2623 and Arp 220 were in excellent agreement with those of Wright et al. (1990), which had been obtained in a previous run with IRCAM on UKIRT. All *K*-band magnitudes and surface brightnesses were corrected for redshifting of the passband and for surface brightness dimming according to the prescription of Glazebrook et al. (1995) who derived a single correction formula applicable to all Hubble types. This correction has a maximum value of -0.11 mag for the present sample, and a mean of -0.06 mag. For the present paper, the final stage of data reduction was to obtain multi-aperture photometry with circular software apertures, regardless of the ellipticity of the galaxies, for comparison with the similar measures taken by Mobasher et al. (1999) to derive $\log D_K$ values (described in Section 6.3 below) for their sample of ellipticals. We did this for the mergers by using the Starlink routine APERADD, centring the apertures using the CENTROID package with a sampling window of 9×9 pixel. Aperture sizes were iterated to find the value within which the mean galaxy surface brightness was 16.5 mag arcsec^{-2} at K, as used by Mobasher et al. (1999). Column 4 of Table 1 gives the derived $\log D_K$ values, where D_K is measured in arcsec, corrected to the distance of the Coma cluster for direct comparability with the Coma ellipticals. This correction was done assuming an unperturbed Hubble flow and a Coma cluster redshift of 6942 km s^{-1} Mpc^{-1}. A Hubble constant of 75 km s^{-1} Mpc^{-1} was assumed throughout. Column 6 gives the log of the effective diameter A_e, in arcsec and again corrected to the Coma distance. A_e (the diameter encompassing half the total light for a pure $R^{1/4}$ profile) was approximated by a Petrosian diameter (Petrosian 1976) with index $\eta = 1.39$ (Kjaergaard, Jorgensen & Moles 1993). η is the difference between the surface brightness at a given radius and the mean surface brightness within that radius. This definition of A_e was used as it is insensitive to departures from pure $R^{1/4}$ profiles, and should be relatively unaffected by fading in the surface brightness of galaxies. Column 7 gives the mean K-band surface brightness within the diameter A_e.

The other data listed in Table 1 are catalogued name (column 1), number in the Arp (1966) list of peculiar and disturbed galaxies (column 2), total K-band absolute magnitude (column 3), and best-fitting power-law index to the light profile, as described in Section 6.1 below (column 5).

5.2 Spectroscopy

Initial data reduction was done at the telescope, using an automatic reduction process to dark- and bias-subtract all frames, to flat-field using internally generated lamp flats, and to ratio by an A-star spectrum to remove telluric absorptions. The galaxies were slid up and down the slit to facilitate sky subtraction, and the processed 'reduced group' frames contained two spectra, one positive and one negative, following the automatic subtraction of spectra taken at the two positions. Known bad pixels in the array were automatically set to 'magic' values, so that they would be ignored in subsequent reduction, but it was also necessary to identify additional bad pixels and cosmic ray hits in the reduced groups. Wavelength calibration was done using an argon arc lamp in CGS4. No spectrophotometric calibration was attempted, as it was not required for this project.

The positive and negative spectra were then extracted from each reduced group frame and subtracted to give the final galaxy spectrum. For the template star BS 4737, a long-baseline spectrum was obtained by observing at 12 grating positions. These spectra were combined using the ADJOIN routine in FIGARO, giving the final stellar template spectrum.

The final stage of data reduction was to determine the velocity dispersions in the galaxy mergers from the Doppler smoothing of the CO absorption. This absorption has an intrinsically steep edge at 2.293 μm which makes it sensitive to such effects. Following Doyon et al. (1994b) and Gaffney et al. (1995) we assumed that the velocity smoothing function can be approximated by a Gaussian of the form $f(x) = \exp[-(x^2/2\sigma^2)]$, where x is the displacement in velocity from the systemic velocity of the galaxy and σ is proportional to the width of the Gaussian and hence the velocity dispersion. To determine the velocity dispersion, we convolved the template spectrum of BS 4737 with Gaussians of different widths, and determined the best fit of the resulting spectrum to the measured galaxy spectrum. In each of these fits, the free parameters were a multiplicative scaling of the spectral fluxes, an additive constant to the spectral fluxes, and a wavelength shift owing to redshift differences between the galaxy and template star. In each case, well-defined minima were found in the reduced χ^2 of the fits with respect to each of the four free parameters. Having identified the best fit, errors were calculated for the width of the velocity Gaussian by freezing the other parameters and changing the Gaussian width until the reduced χ^2 increased by the factors corresponding to 1σ and 2σ uncertainties.

Table 2 lists parameters derived from spectroscopic measurements. Column 1 gives the galaxy name, column 2 the catalogued recession velocity, and column 3 the recession velocity derived from the spectroscopic fits described above, quite independently of the catalogued recession velocity. Good agreement is found with the catalogued recession velocity values, giving confidence in the fitting process. Column 4 of Table 2 gives the derived velocity dispersion with 1σ error, and column 5 the spectroscopic CO index, which is discussed further in Section 6.3 below.

6 ANALYSIS

6.1 Light profiles

We first address the question of whether the elliptical-like light profiles found for some mergers could be due to pre-existing bulges that have survived the merging process. Fig. 1 shows a comparison of the best-fitting indices of the K-band light profiles of the mergers (plotted as circles) with those for the bulges of spirals (crosses) of Hubble types Sa–Sd (Seigar & James 1998), and two ellipticals (squares), NGC 5845 and 6023. The fitted

Table 1. Galaxy names and photometric parameters.

Galaxy name	Arp No.	M_K	Log D_K	Profile index	Log A_e	$\langle SB_K \rangle_e$
IC 883	193	−24.05	1.226	0.36 ± 0.05	1.21 ± 0.05	16.44
IC 4553	220	−24.46	1.322	0.24 ± 0.09	1.22 ± 0.03	16.10
Mrk 231	–	−27.08	1.903	0.17 ± 0.05	1.00 ± 0.05	14.77
Mrk 273	–	−25.19	1.497	0.14 ± 0.05	1.24 ± 0.02	15.48
NGC 2623	243	−23.85	1.207	0.10 ± 0.05	0.94 ± 0.09	15.47
NGC 3509	335	−24.24	1.008	0.025 ± 0.05	> 1.59	> 18.3
NGC 4194	160	−23.04	1.093	0.20 ± 0.05	0.65 ± 0.03	14.71
NGC 6052	209	−23.44	0.923	0.83 ± 0.5	1.36 ± 0.01	17.58
NGC 6090	–	−24.49	1.331	(0.05 ± 0.05)	1.35 ± 0.03	16.53
NGC 6240	–	−25.85	1.640	0.11 ± 0.05	1.55 ± 0.03	16.17
NGC 7252	226	−24.57	1.372	0.28 ± 0.05	1.21 ± 0.02	15.90

Table 2. Spectroscopic parameters.

Galaxy name	Catalogued recession velocity (km s^{-1})	Derived recession velocity (this work)	Velocity dispersion	CO_{sp}
IC 883	7000	7040	206 ± 90	0.25[2]
IC 4553	5434	–	150 ± 21[3]	0.32[1]
Mrk 231	12 651	–	–	−0.02[1]
Mrk 273	11 326	11 308	160 ± 60	0.23[1]
NGC 2623	5535	–	–	0.24[1]
NGC 3509	7704	–	–	–
NGC 4194	2506	2523	104 ± 25	–
NGC 6052	4716	–	–	–
NGC 6090	8795–9062	8929	50 ± 20	0.30[1]
NGC 6240	7339	–	359 ± 21[3]	0.29[1]
NGC 7252	4688	4743	123 ± 19	–

References: [1]Ridgway et al. (1994); [2]Goldader et al. (1995); [3]Doyon et al. (1994b).

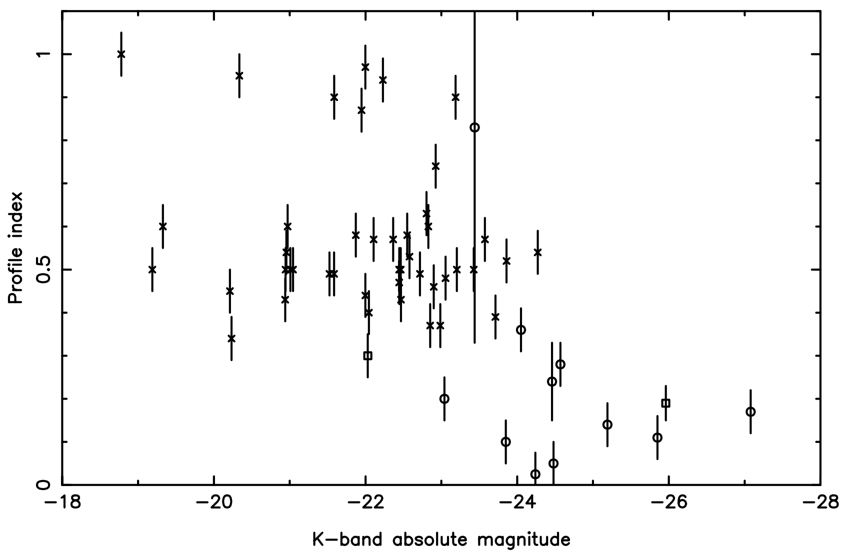

Figure 1. The best-fitting profile index versus the *K*-band absolute magnitude for spiral bulges (crosses), ellipticals (squares) and mergers (circles).

profiles are generalized de Vaucouleurs profiles, and the index plotted is $1/n$ in the $R^{1/n}$ relation, such that a true de Vaucouleurs profile would correspond to 0.25. The errors were calculated by omitting zero, one, two and three central points from the profiles and redoing the fits. This excluded a circular area of radius up to 3.7 arcsec, significantly larger than the seeing size, and generally had little impact on the measured indices. The spiral galaxy indices generally lie between 0.4 and 1.0, with some evidence for a bimodal distribution with ~ 0.5 and ~ 1.0 as preferred values. Similar results were found by de Jong (1996). However, the mergers show significantly brighter total luminosities and cuspier light profiles, with indices lying close to the value of 0.25, as do the two ellipticals for which we have *K*-band imaging. However, not all of the mergers plotted are actually well fitted by a de Vaucouleurs profile, with some having significant ripples and irregularities in their profiles. The important result from Fig. 1 is that even these systems show at least the degree of central light concentration expected of an elliptical, and their light distributions and luminosities are not those expected of pre-existing spiral bulges, or of galaxy discs. Indeed, there is even some evidence that the mergers have lower indices and cuspier profiles even than ellipticals, which may be evidence of an additional, centrally concentrated component in the *K*-band light, resulting from a nuclear starburst. This possibility is discussed further in Section 6.3.

The referee commented that there appears to be a trend in profile index with absolute magnitude, and suggests that the lower values found for the mergers may simply reflect a selection bias, since the mergers are significantly more luminous than the bulges, on average. However, if there is such an effect, it does not appear to be strong enough to cause the result that we find. Regressing index on absolute magnitude, there is a weak trend for both the bulges and mergers, in the sense that more luminous systems have somewhat lower indices. However, the correlations have significances of less than 5 per cent in both cases. Extrapolating the trend found for bulges to the mean absolute magnitude of the mergers predicts that the average profile index for the mergers should be 0.51, whereas the average of the measured indices is 0.23. Thus the mergers genuinely seem to be offset to lower profile indices than bulges, even if we were to compare with bulges of similar luminosity (which do not seem to exist in any case).

The merger with the large error bar in Fig. 1 is NGC 6052, which has a highly irregular structure, even in *K*-band light. Since the errors are estimated from fitting the profile over different radial ranges, it would appear that the unusual and highly irregular profile of NGC 6052 is particularly sensitive to such changes. It is clear that this galaxy bears no resemblance to an elliptical galaxy, and appears quite different from the other mergers.

6.2 Velocity dispersions

Fig. 2 shows the range of velocity dispersions found for ellipticals and bulges by Whitmore, McElroy & Tonry (1985). These are split into ellipticals (dashed line), lenticulars (solid line) and spirals (dotted line). The measured velocity dispersions for the mergers are also marked at the top of Fig. 2. It can be seen that the majority of mergers have velocity dispersions between 100 and $200\,\mathrm{km\,s^{-1}}$, with a mean of $164 \pm 35\,\mathrm{km\,s^{-1}}$, where the standard error on the distribution is quoted. This compares with mean velocity dispersions of $222 \pm 5\,\mathrm{km\,s^{-1}}$ for ellipticals, $190 \pm 4\,\mathrm{km\,s^{-1}}$ for lenticular bulges and $142 \pm 4\,\mathrm{km\,s^{-1}}$ for spiral bulges, from values in the Whitmore et al. (1985) compilation. NGC 6090 has the lowest velocity dispersion of any of the mergers, and this may well be related to the fact that it has two widely separated nuclei. Thus for this galaxy we are almost certainly seeing the velocity dispersion of one of the pre-existing nuclei, and this value is likely to be significantly lower than the disperson of the final, relaxed merger remnant. At the other extreme, NGC 6240 has a velocity dispersion larger than those of any of the spiral galaxy bulges in the Whitmore et al. (1985) compilation, and the value is indeed in the high-velocity tail of the distribution even for elliptical galaxies. Again, this may not represent the final virialized velocity dispersion of this system. For example, there may be superposed components with different systemic velocities along the line of sight, which would be impossible to distinguish using the present data. Such effects cannot be gross, since then the spectroscopy would resolve two separate CO absorption features. However, given the width of the CO feature and limited signal-to-noise ratio of the present data, no strong constraints can be placed.

The distribution of velocity dispersions of the merger sample is shown by a Kolmogorov–Smirnov test to be formally consistent with those of both spiral bulges and ellipticals, and so our velocity data alone do not permit any significant test of the dynamical evolution of mergers. In this, we differ somewhat from Shier & Fischer (1998), who conclude that their velocity dispersion measurements are not consistent with the values expected for L_* elliptical galaxies, since, apart from NGC 6240, the highest velocity dispersion that they measure is $151\,\mathrm{km\,s^{-1}}$.

6.3 Parameter correlations

A strong test of the merger hypothesis is made possible by the parameter correlations resulting from the 'Fundamental Plane' of elliptical galaxies (Dressler et al. 1987; Djorgovski & Davis 1987), since we know that any forming elliptical will have to arrive on this plane. This describes the tight two-dimensional locus occupied by elliptical galaxies in the three-dimensional space defined by velocity dispersion, luminosity and scale-size. These latter two parameters can be conveniently grouped together, and Dressler et al. (1987) found that a particularly useful quantity was D_n, the diameter of a photometric aperture within which the mean surface brightness of the galaxy has some value n. Dressler et al. took n to be $20.75\,\mathrm{mag\,arcsec^{-2}}$ in the optical B passband, and found a very tight correlation between the resulting D_n values and velocity dispersion. Mobasher et al. (1999) have examined the equivalent relation (which they term the D_K–σ relation) using K-band photometry of elliptical galaxies in the Coma cluster, and find a small scatter of 0.076 dex in the relation, similar to the optical D_n–σ relation. They also present a plot which explicitly shows an edge-on projection of the K-band Fundamental Plane, thus reducing the scatter even below that of the D_K–σ relation. Here the plotted quantities are $1.38\log\sigma + 0.3\langle \mathrm{SB}_K\rangle_\mathrm{e} + c_1$ versus $\log A_\mathrm{e}$, where A_e is the effective diameter and $\langle \mathrm{SB}_K\rangle_\mathrm{e}$ the mean surface brightness within this diameter. The data set of Mobasher et al. thus provides an excellent way to test whether our mergers obey the same parameter correlations as do elliptical galaxies, since all the parameters required for these relations are provided by our K-band photometry and spectroscopy.

D_K values were calculated using circular aperture photometry on the K-band images, and by finding the size in arcseconds of a circular aperture that enclosed a mean surface brightness of $16.5\,\mathrm{mag\,arcsec^{-2}}$. This surface brightness, and the use of circular apertures, was identical to the procedure followed by Mobasher et al. (1999), and so the results should be directly comparable. Fig. 3 shows the D_K–σ relations for Coma ellipticals (crosses) and for the mergers (circles). In both axes, the quantities actually plotted are logarithms to base 10. The ellipticals show the expected correlation, whereas the mergers scatter well above this locus. This implies that the mergers have anomalously low velocity

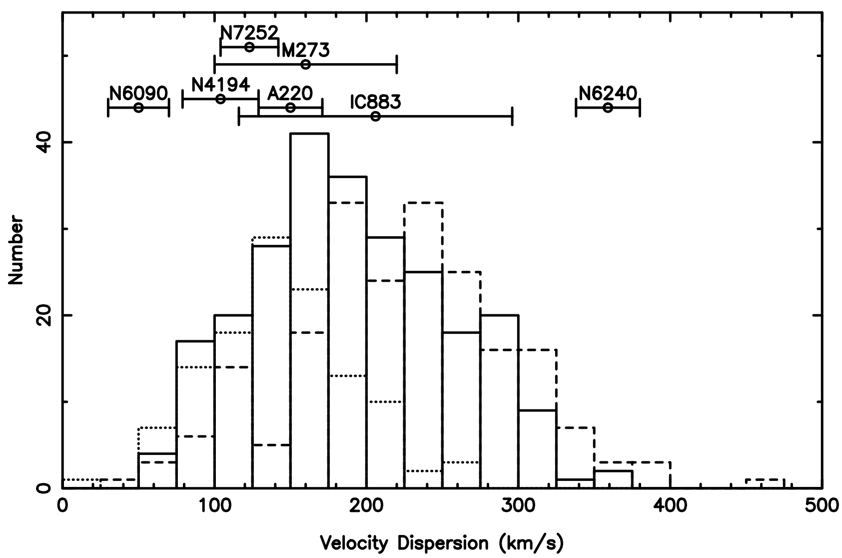

Figure 2. The distribution of velocity dispersions taken from Whitmore et al. (1985), showing ellipticals (dashed line), lenticular bulges (solid line) and spiral bulges (dotted line). The measured velocity dispersions for the mergers are indicated at the top of the figure.

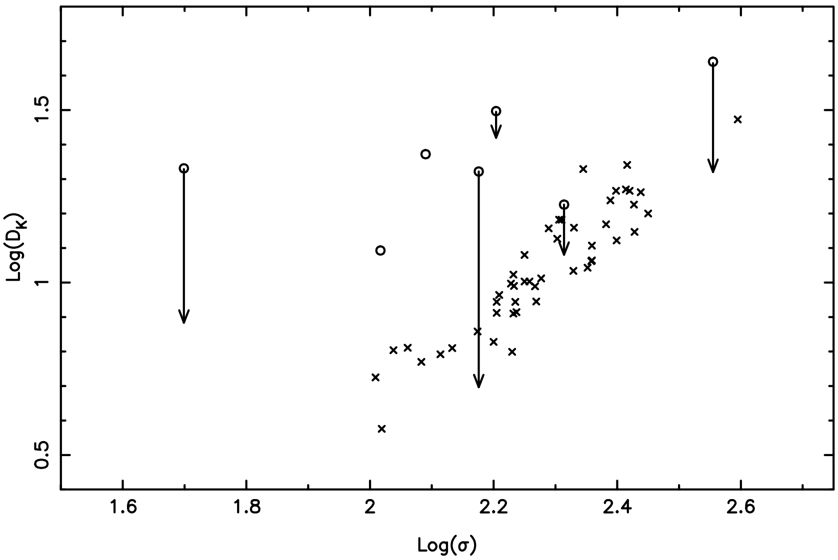

Figure 3. The D_K–σ relation for Coma ellipticals (crosses) taken from Mobasher et al. (1999), and for the present sample of mergers (circles). The arrows show the effect of K-band fading inferred from CO indices as explained in Section 6.3.

dispersions, or anomalously large D_K diameters, or a combination of both, when compared with the Coma ellipticals.

A similar result is shown in Fig. 4, which compares the near-infrared Fundamental Plane of Coma ellipticals with the present merger sample. Again the elliptical galaxies show a very tight correlation, whereas the mergers scatter away from the Fundamental Plane in the same sense as was found from Fig. 3. We will now discuss whether the offset is likely to be due to anomalous velocity dispersions or surface brightnesses in the mergers.

As noted above, the distribution of velocity dispersions of the merger sample is consistent with that of elliptical galaxies (formally the means of the two distributions differ by 1.6σ but the Kolmogorov–Smirnov test shows the distributions to be indistinguishable), and is unlikely to evolve further in these relaxed central regions. This consistency is confirmed by Fig. 3, with the possible exception of NGC 6090, which may evolve to a higher velocity dispersion as the two nuclei relax together. For the remainder of the mergers, any plausible evolution on to the elliptical locus in Fig. 3 seems likely to be predominantly in the D_K direction, and in every case would have to be in the sense of making the galaxies become smaller, at the same mean surface brightness level. This is quite plausible, given that mergers are widely acknowledged to be linked to highly luminous bursts of massive star formation (e.g. Joseph & Wright 1985; Barnes & Hernquist 1991; Solomon, Downes & Radford 1992; but see also the counter-arguments of Thronson et al. 1990). Such a starburst will result in a temporarily enhanced luminosity and surface brightness of the system, and in the K band this is likely to result principally from emission from supergiant stars. Thus we would argue that the most likely future evolution of the mergers will shift them vertically in Fig. 3, in the direction of smaller D_K values. Assuming the starburst population to be well mixed with the older stars, this fading will not affect the A_e-values, and will shift points vertically upwards in Fig. 4, again consistent with moving them on to the Fundamental Plane defined by Coma ellipticals. We will now estimate the likely size of this effect.

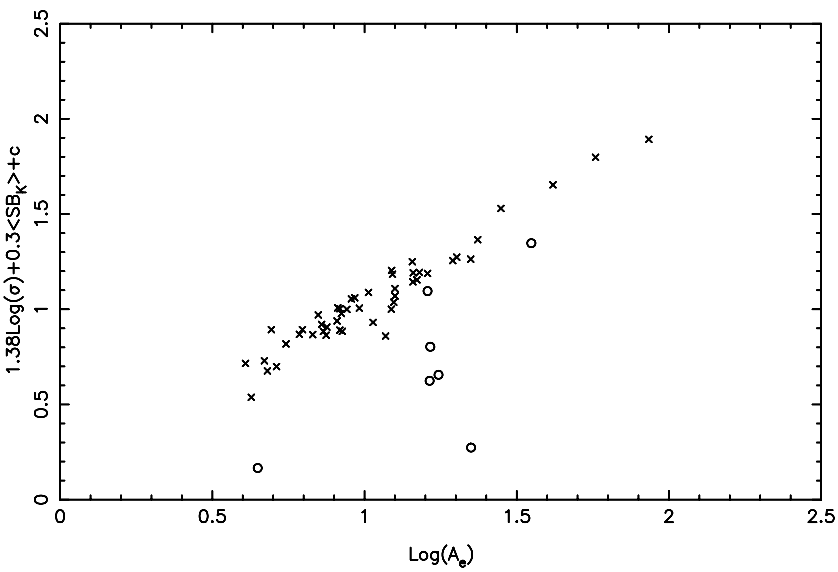

Figure 4. The Fundamental Plane relation for Coma ellipticals (crosses) taken from Mobasher et al. (1999), and for the present sample of mergers (circles).

The photometric contribution of supergiants in mergers can be quantified from the depth of the 2.3-μm CO absorption feature, which is characteristic of such stars (Doyon, Joseph & Wright 1994a; Ridgway, Wynn-Williams & Becklin 1994; Goldader et al. 1995). Using a method described by Doyon et al. (1994a), it is possible to use low-resolution K-band spectroscopy to make an estimate of the fraction of K-band light contributed by the starburst population in a galaxy from the depth of the CO feature. This method assumes that the K-band light has contributions from an old stellar population with a small CO index, and a starburst population with a much larger CO index. From the observed index, which lies between these extremes, one can then solve for the fractional mix of the two populations. This simple form of population synthesis was applied to the five mergers for which CO indices were available [Mrk 273, Arp 220, NGC 6090 and NGC 6240 from Ridgway et al. (1994); IC 883 from Goldader et al. (1995)], assuming a spectroscopic CO index (see Doyon et al. 1994a for a definition) of 0.2 for the old population and 0.34 for a pure starburst.

It was found that the starburst fraction varied from providing only ~20 per cent of the K-band luminosity in Mrk 273, to ~85 per cent in Arp 220. We then made the simplifying assumptions that all of this starburst population would ultimately disappear, and that this would uniformly depress the surface brightness of the galaxy in the K band. It was then straightforward to predict the effect of such fading on the D_K-values for these five mergers, and the results are shown as arrows in Fig. 3. Clearly, this correction moves the points towards the elliptical locus, and the movement is of the right order to explain the present discrepancies. The equivalent fading vectors in Fig. 4 would shift the points vertically upwards by between 0.1 and 0.6 in the quantity plotted on the y-axis, again of the correct order to shift points on to the Fundamental Plane. The corresponding arrows are not shown in this figure to avoid confusing the plot.

A further test of this fading hypothesis is shown in Fig. 5, where $\log A_e$ is plotted against $\log\,\sigma$. Given the definition of A_e as a Petrosian diameter, it should be relatively unaffected by fading, and certainly far less so than D_K and $\langle SB_K \rangle_e$. Given this, it is reassuring to see that the distribution of mergers is much more consistent with that of ellipticals in this figure than in Figs 3 and 4, and that the one very discrepant point, the double-nucleus system NGC 6090, is offset to lower $\log\,\sigma$, as suggested earlier.

If there are red supergiants in the numbers necessary to explain the observed CO indices, then for any plausible star formation history and initial mass function it is to be expected that younger OB stars should also be present. This is confirmed for the mergers plotted with arrows in Fig. 3: Goldader et al. (1997) find strong Brackett γ emission from all five, consistent with the presence of OB stars.

7 DISCUSSION

A study of the dynamics of mergers was undertaken by Lake & Dressler (1986), who compared the luminosity–velocity dispersion (L–σ) relation with that of ellipticals (Faber & Jackson 1976). They combined B and V photometry from the literature with Reticon spectroscopy of the Ca triplet, and found a remarkably good agreement between the distribution of velocity dispersions and optical luminosities for mergers and ellipticals. This result was argued to be at variance with a simple dynamical model, which predicted that merging should not lead to an increase in velocity dispersion. Thus they concluded that the merging process must involve significant dissipation for the merger products to follow the L–σ relation as found.

The L–σ relation is very closely related to the D_n–σ relation that we have investigated. The apparent difference in results is probably due to the merger sample selection. The only merger in common between the two studies is NGC 7252, and this is possibly the most evolved merger in our sample, but the youngest merger observed by Lake & Dressler. The majority of their objects are recognizable as elliptical galaxies, but with peculiarities such as strong shells and ripples which make it likely that these are mergers in the late stage of the relaxation process, which is only beginning for most of our galaxies. Thus it is not surprising that different results are found by the two studies.

Shier & Fischer (1998) have performed a K-band Fundamental Plane analysis of their merger sample, like that of the present paper, and reach very similar conclusions. They also find that most of the mergers are displaced from the plane defined by

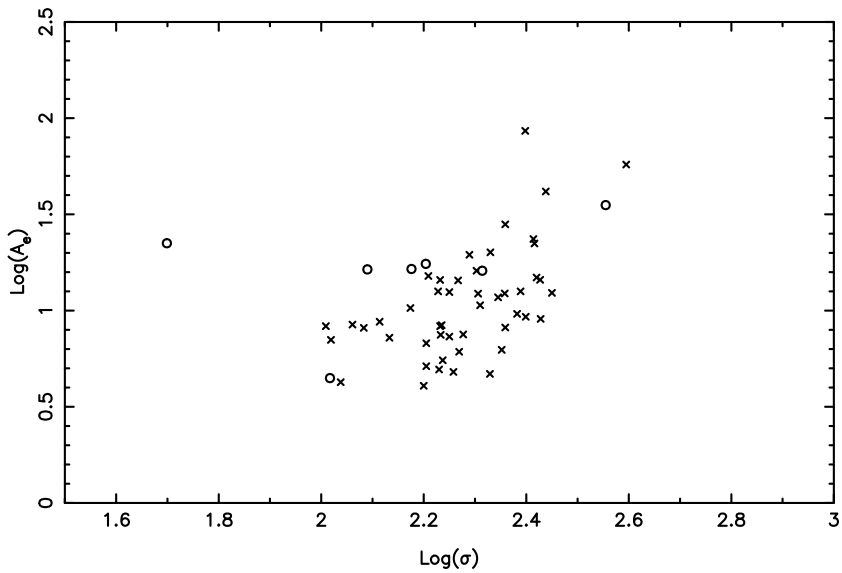

Figure 5. Log A_e versus $\log\,\sigma$ for Coma ellipticals (crosses) taken from Mobasher et al. (1999), and for the present sample of mergers (circles).

ellipticals, in the sense of being bright for a given velocity dispersion. From a population synthesis argument, they estimate that the mergers are likely to fade by 1.5–2.0 mag in the K band during the next 3 Gyr, and that this fading will place them on or near the elliptical locus, assuming no other scale-size or dynamical changes.

8 CONCLUSIONS

The principal conclusions of this study are as follows. We confirm that, in terms of their near-infrared photometric properties, ongoing galaxy mergers more nearly resemble elliptical galaxies than they do spiral bulges. Even those poorly fitted by a de Vaucouleurs profile show a 'cuspy' light distribution which is likely to smooth into an elliptical-like profile through relaxation processes. Using velocity dispersions alone we are unable to distinguish whether mergers more closely resemble bulges or ellipticals, but this is unsurprising given the small number of mergers in our sample and the extensive overlap between bulge and elliptical σ-distributions. A clear discrepancy is found between the Fundamental Plane distributions and D_K–σ relations of mergers and ellipticals, however. We suggest that this may be due to a short-lived population of supergiant stars temporarily increasing the surface brightness of the mergers, and find evidence for such a population at approximately the predicted level from literature measurements of the CO absorption strength.

It is clear that significant improvements on these results are attainable with existing and planned instrumentation. An intriguing possibility is that it may be possible, by combining samples of young and old mergers, to map out an evolutionary sequence from the highly distorted and dusty systems to the relaxed, old-star-dominated elliptical galaxies, from their positions in the Fundamental Plane parameter space. Key issues here would be the relative importance of star formation, stellar evolution effects, dynamical relaxation and dissipation in the formation of the Fundamental Plane.

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