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Measurement of non-axisymmetry in centres of advanced mergers of galaxies

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ABSTRACT

We measure the non-axisymmetry in the luminosity distribution in the inner few kpc of the remnants of advanced mergers of galaxies with a view to understand the relaxation in the central regions. For this, we analyse the images from the Two-Micron All-Sky Survey (2MASS) archival data for a selected sample of 12 merging galaxies, which show signs of interaction but have a single nucleus. The central regions are fitted by elliptical isophotes whose centres are allowed to vary to get the best fit. The centres of isophotes show a striking sloshing pattern with a spatial variation of up to 20–30 per cent within the central 1 kpc. This indicates mass asymmetry and a dynamically unrelaxed behaviour in the central region. Next, we Fourier-analyse the galaxy images while keeping the centre constant and measure the deviation from axisymmetry in terms of the fractional Fourier amplitudes (A_1, A_2, etc.) as a function of radius. All the mergers show a high value of lopsidedness (up to $A_1 \sim 0.2$) in the central 5 kpc. The $m = 2$ asymmetry is even stronger, with values of A_2 up to $\sim$0.3, and in three cases these are shown to represent bars. The corresponding values denoting non-axisymmetry in inner regions of a control sample of eight non-merger galaxies are found to be several times smaller.

Surprisingly, this central asymmetry is seen even in mergers where the outer regions have relaxed into a smooth elliptical-like $r^{1/4}$ profile or a spiral-like exponential profile. Thus, the central asymmetry is long lived, estimated to be $\sim$1 Gyr, and hence lasts for over 100 local dynamical time-scales. These central asymmetries are expected to play a key role in the future dynamical evolution of the central region of a merger, and can help in feeding of a central active galactic nucleus.

Key words: galaxies: evolution – galaxies: kinematics and dynamics – galaxies: interactions – galaxies: photometry – galaxies: structure.

1 INTRODUCTION

Interactions and mergers of galaxies are now known to be common and these can significantly affect the dynamics and evolution of the merging galaxies (Wielen 1990; Barnes & Sanders 1999). The work so far has mainly concentrated on the intermediate radial range of a few kpc – few × 10 kpc; observationally, the mergers have been shown to result in an elliptical-like $r^{1/4}$ profile as was first shown for NGC 7252 by Schweizer (1982), and later by others for larger samples (Wright et al. 1990; Stanford & Bushouse 1991; Chitre & Jog 2002). Interestingly, in half the sample of mergers showing a single nucleus but evidence for tidal interaction as studied by Chitre & Jog (2002), the remnants even showed an exponential profile like a disc, while a few showed no-fit implying unrelaxed outer regions. The galaxies with disc-like profiles are peculiar and have elliptical-like high velocity dispersion and could have thick discs, as shown for two galaxies (Jog & Chitre 2002). Theoretically, the evolution of mergers leading to a relaxed elliptical-like remnant has been well studied by N-body simulations (e.g. Barnes 1992; Bournaud, Jog & Combes 2005b). Recent simulations of unequal-mass mergers can reproduce the above, relaxed disc-like remnants (Bournaud, Combes & Jog 2004; Naab & Trujillo 2006), while the transition between the elliptical- and spiral-like remnants is shown to occur for a narrow mass-range of 3:1–4.5:1 (Bournaud et al. 2005b). An inclusion of gas has also been shown to result in a disc-like remnant in some cases (Volker & Hernquist 2005).

However, despite its obvious importance for the evolution of the central regions, the luminosity distribution in the central regions of mergers has not been studied systematically so far. A few mergers where this has been studied, such as NGC 3921 (Schweizer 1996) and Arp 163 (Chitre & Jog 2002), show a wandering or meandering

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centre for the isophotes. However, there has been no study so far to measure the non-axisymmetric amplitudes in mergers.

In this paper, we systematically study the asymmetry in the central few kpc of advanced mergers of galaxies. The recent availability of near-infrared (near-IR) data [including the excellent archival Two-Micron All-Sky Survey (2MASS) data base] allows one to study the main underlying mass distribution directly in the central regions of mergers for a large sample of galaxies. In the near-IR, the dust extinction is low and the luminosity distribution directly traces the old stellar component, and hence the main mass component.

The mergers involve a patently non-axisymmetric configuration, especially at large radii (of 20–30 kpc), outside of the main merged body where spectacular tidal features are seen. Even the inner optical image is patchy, especially as seen in the blue light, where the dust obscuration plays a major role. Hence, naively it would seem that they would show asymmetry in the central regions of few kpc as well. However, the advanced mergers do show some degree of relaxation as evident from their merged centres, and their relaxed outer profiles ($\sim$10 kpc or so), as seen in the near-IR, as discussed above. Further, the dynamical time-scales are smaller in the inner regions and hence they would be expected to be more relaxed than the outer parts. Thus, it is interesting to measure the values of non-axisymmetry in the central regions of mergers. For example, the values of central lopsidedness can provide an important diagnostic for the degree of relaxation in the central regions of a merging pair of galaxies.

Our earlier study of Arp 163 (Chitre & Jog 2002) showed a wandering centre. This is a no-fit merger – which cannot be fit by an elliptical or an exponential fit, where the outer regions are not relaxed. In this paper, we measure the central asymmetry in the mergers with no-fit in the outer regions as well as in the other mergers which show relaxed outer profiles. Thus, this study is expected to provide information on the relaxation in the inner regions, and also reveal the correlation if any of the central asymmetry or degree of relaxation with that in the outer regions.

We do a detailed isophotal analysis of the galaxy images and study the sloshing of the isophotal centres quantitatively, and then Fourier-analyse the images and obtain the amplitudes for lopsidedness and also for $m = 2$. In three cases, the latter are shown to represent a strong bar.

We show that the lopsidedness is high in all cases, and the magnitude of the central asymmetry is higher in those mergers which are unrelaxed in the outer regions. Interestingly, even galaxies where the outer regions have relaxed into a smooth mass profile still display a fairly strong central asymmetry and hence a non-relaxed central mass distribution.

Section 2 contains a discussion about the sample selection and the basic properties of the sample galaxies. Section 3 contains data analysis and the results for mergers and a comparison with results for a set of non-merger or normal galaxies. Section 4 includes a discussion of the dynamical implications of the results, and a brief summary is given in Section 5.

2 SAMPLE SELECTION

The sample galaxies were chosen to be advanced mergers of galaxies which have already lost their identities and merged into a single nucleus (up to the resolution limit of 2 arcsec in 2MASS), and which still looked disturbed and had signs of recent interaction, such as tidal tails, plumes, etc.; for more details see Chitre & Jog (2002). The galaxies were chosen from the Atlas of peculiar galaxies (Arp 1966) and the Arp–Madore catalogue of southern peculiar galaxies (Arp & Madore 1987).

Our earlier work (Chitre & Jog 2002) showed that these could be divided into three dynamically distinct classes, where the luminosity profiles could be fitted by either a $r^{1/4}$ profile (class I) or an outer exponential (class II) or a no-fit (class III). In the present paper, we have chosen representative examples from each of these classes, with an emphasis on class III which showed sloshing of the inner isophotes even on a visual inspection (Chitre & Jog 2002). Of that sample of 27 galaxies, only those galaxies which had a large enough angular size for non-axisymmetric analysis were chosen. This meant that they should be divisible into at least five to six annular rings, with each ring size about twice the resolution of the 2MASS data, so that a meaningful non-axisymmetric analysis could be carried out. The J-band data were used for this purpose for all the galaxies since the images are deeper in this band allowing for a radial sampling.

This led to a total of eight galaxies to be selected. To this, we added a further four more galaxies from the Arp and Arp–Madore catalogues for which such a non-axisymmetric analysis could be carried out, to supplement our sample, namely, Arp 209, Arp 254, AM 1025-433 and AM 0612-373.

Thus, the total sample used for the present work consists of 12 galaxies divided into three classes as follows:

class I: Arp 221, Arp 222, Arp 225, AM 0612-373;

class II: Arp 162, Arp 212, Arp 224;

class III: Arp 160, Arp 163, Arp 209, Arp 254, AM 1025-433;

The four new galaxies chosen here which were not in our earlier sample fall into class I (AM 0612-373) and class III (Arp 209, Arp 254, AM 1025-433). The luminosity profiles defining the classification of all the galaxies are given below.

For the radial fits and the isophotal analysis, we used the K_s-band data for all galaxies. This is because the dust extinction effects are least important for this band (than say J or H) and hence this is suitable for the central sloshing to be studied via the isophotal analysis.

The 2MASS full-resolution images for extended sources were obtained from the three-dimensional Flexible Image Transport System (FITS) image cubes or from the mosaic images for larger galaxies. The K_s-band images were analysed using the task ELLIPSE within STSDAS.[1] The procedure consisted of fitting elliptical isophotes to the galaxy images and deriving the one-dimensional azimuthally averaged radial profiles for the surface brightness, ellipticity, position angle (PA), etc. based on the algorithm given by Jedrzejewski (1987). The centre, PA and ellipticity were allowed to vary. Ellipses were fit right up to the central pixel. The parameters thus derived, namely the surface brightness profile, the ellipticity and the PA variation, and $x0$, $y0$ – the x- and y-coordinates of the centres were studied.

The resulting surface brightness radial profiles are plotted for all the 12 sample galaxies in Fig. 1. The luminosity profile fitting for eight of these galaxies from our earlier sample has already been done (see fig. 1 in Chitre & Jog 2002). As discussed in that paper, surprisingly, the profiles can be best fit by an outer exponential in four cases; the fit is robust in the sense that the radial range over which the fit is valid is typically two times the disc scalelength or larger, and the error bars are small. The values of the de Vaucouleurs scalelength, R_e (for class I galaxies), and the exponential disc scalelength, R_D (for class II galaxies) are given in Table 1. This figure defines the classification for the four new galaxies as follows: AM 0612-373 (class I), Arp 209, Arp 254 and AM 1025-433 (class III).

[1] STSDAS is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

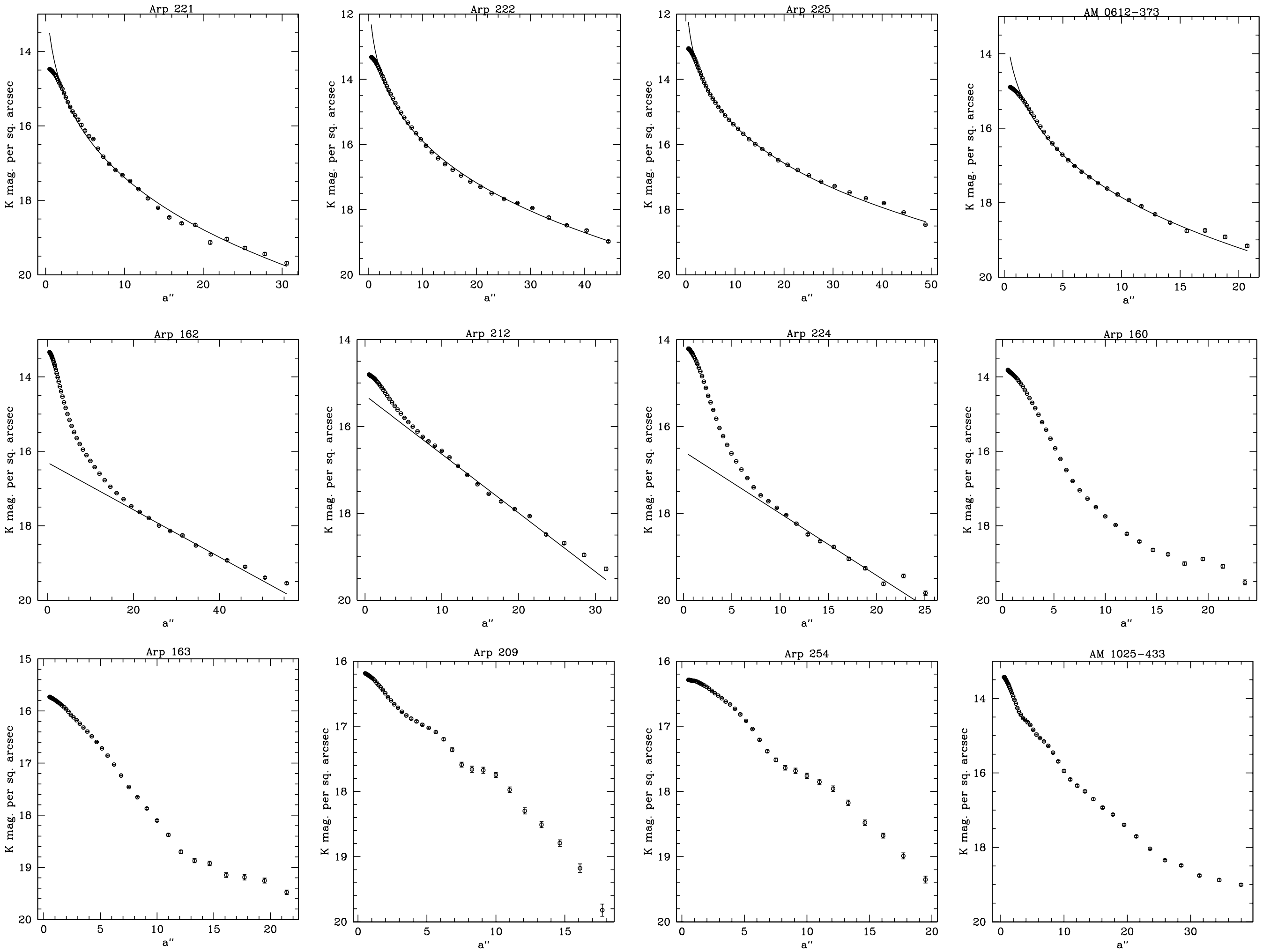

Figure 1. The K_s-band magnitude in mag arcsec^{-2} is plotted against the semimajor axis, a, in arcsec. The first four galaxies (Arp 221, Arp 222, Arp 225 and AM 0612-373) are well fit by a $r^{1/4}$ law (class I); the next three (Arp 162, Arp 212 and Arp 224) are well fit by an outer exponential (class II) and the last five are no-fit galaxies (class III).

Table 1. Basic data on mergers of galaxies.

Name	Alt. name	R_e, R_D (kpc)	Velocity (km s^{-1})	1 arcsec[a] (pc)
Class I				
Arp 221	–	5.76±0.41	5546	358
Arp 222	NGC 7727	2.83±0.46	1855	125
Arp 225	NGC 2655	3.26±0.38	1404	91
AM 0612-373	–	11.26±0.45	9864	620
Class II				
Arp 162	NGC 3414	1.56±0.04	1414	87
Arp 212	NGC 7625	0.85±0.03	1633	104
Arp 224	NGC 3921	2.91±0.21	5838	383
Class III				
Arp 160	NGC 4194	–	2442	168
Arp 163	NGC 4670	–	1069	78
Arp 209	NGC 6052	–	4716	305
Arp 254	NGC 5917	–	1904	123
AM 1025-433	NGC 3256	–	2814	182

[a]Using $H_0 = 75$ km s^{-1} Mpc^{-1}.

Table 1 lists the sample chosen, distributed in terms of this classification, with all the relevant astronomical parameters (galaxy name, Alternate name, R_e, R_D, velocity and 1 arcsec in pc) for the three classes showing the different radial fits.

3 DATA ANALYSIS AND RESULTS

3.1 Isophotal analysis: sloshing

The isophotal analysis of the images is carried out as described in the last section. The centre, PA and ellipticity were allowed to vary to obtain the best fit by ellipses to the galaxy image.

In Fig. 2, we plot a block of four diagrams for each galaxy, which shows the centres of the isophotes ($x0$, $y0$ versus a, the semimajor axis of the elliptical isophote (in units of kpc). Also shown are the ellipticity and the PA versus a, the semimajor axis. Clearly, in most cases, the centres of the isophotes do not remain constant. Instead, they show a wandering or a sloshing behaviour. This indicates a dynamically unrelaxed central mass distribution. In general, the sloshing is higher in the class III galaxies which are also unrelaxed in the outer regions. This is confirmed by a quantitative measurement of normalized sloshing within $a = 1$ kpc, which is given as

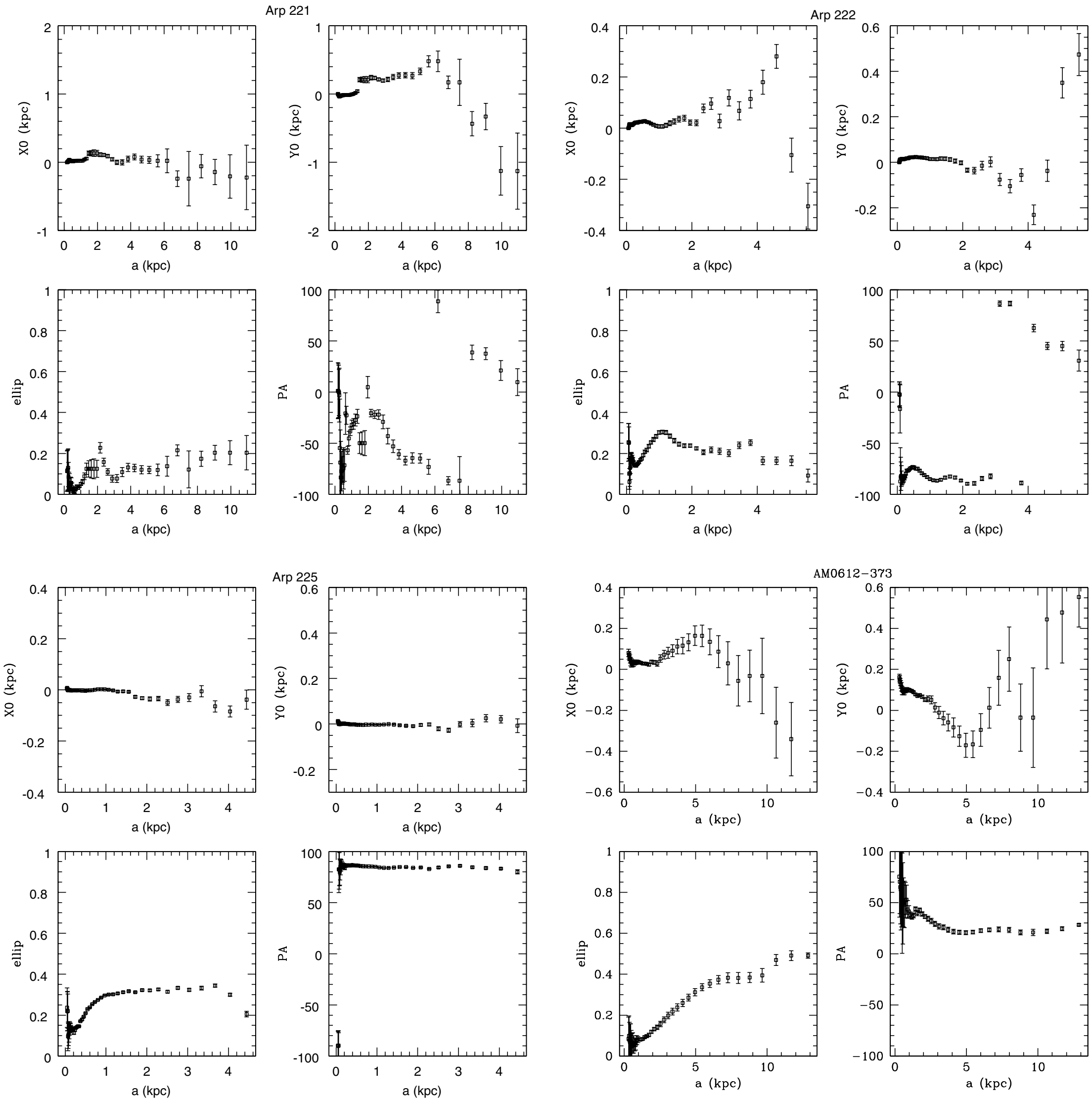

Figure 2. Plots of isophotal analysis for the K_s-band data for the sample galaxies. For each case, we plot a block of four plots, showing the centre $x0$, $y0$ versus the semimajor axis a of the fitted isophotes, and also the ellipticity and the PA versus a. All the galaxies on this page are class I galaxies. Arp 162, Arp 212 and Arp 224 are class II type galaxies, while Arp 160 is a class III type galaxy; it shows a larger sloshing of the centre ($x0$, $y0$) of isophotes. The last four galaxies shown are class III type and they show larger sloshing than shown by class I or II.

average of $\{[(x - x0)^2 + (y - y0)^2]\}^{1/2}/a$–see Table 2. This allows a comparison of sloshing seen in the various classes of galaxies.

3.2 Non-axisymmetry: Fourier amplitudes

The images from 2MASS of mergers were Fourier-analysed to obtain the amplitudes and phases of the Fourier components $m = 1$, 2, 3 and 4, measured with respect to a constant centre. A similar approach has been used in the past to divide the near-IR images of normal galaxies into radial bins, and measure the deviation from axisymmetry in terms of the fractional Fourier amplitudes, such as A_1 and A_2, measured with respect to A_0, the average amplitude, where A_1 denotes the amplitude for lopsidedness ($m = 1$) and A_2 denotes the amplitude for bars or disc ellipticity or spirals (e.g. Rix & Zaritsky 1995; Laurikainen, Salo & Rautiainen 2002; Buta et al. 2005).

In our analysis, the centre is kept constant and the Fourier analysis is carried out over annular rings with respect to this centre. For this, we sum up the pixel values in the radial bins so that the complete 2D data is used and we do not try to fit a curve. This procedure is similar to the one used by Rix & Zaritsky (1995). The resulting A_1 and A_2 amplitudes for $m = 1$ and 2 are better indicators of mass asymmetry measured with respect to the constant centre (than the usual boxiness etc. for an isophote), especially since the centres of isophotes show a lot of sloshing in the case of mergers. For example, it is easy to see that if we use the standard isophotal analysis, then the azimuthal average taken over an isophotal contour with respect to the isophotal centre would give a zero average lopsidedness since the average of $\cos\phi$ would be zero.

Thus, for measuring the non-axisymmetric mass distribution, we need to keep the centre constant and then measure the Fourier amplitudes over annular radial bins, for this a special procedure was adopted which is described below.

First, the x- and y-coordinates of the centre of the galaxy (or the stellar centre) were determined using the task ‘IMEXAM’ in IRAF and plotting the radial profile. Once this pixel value was found in

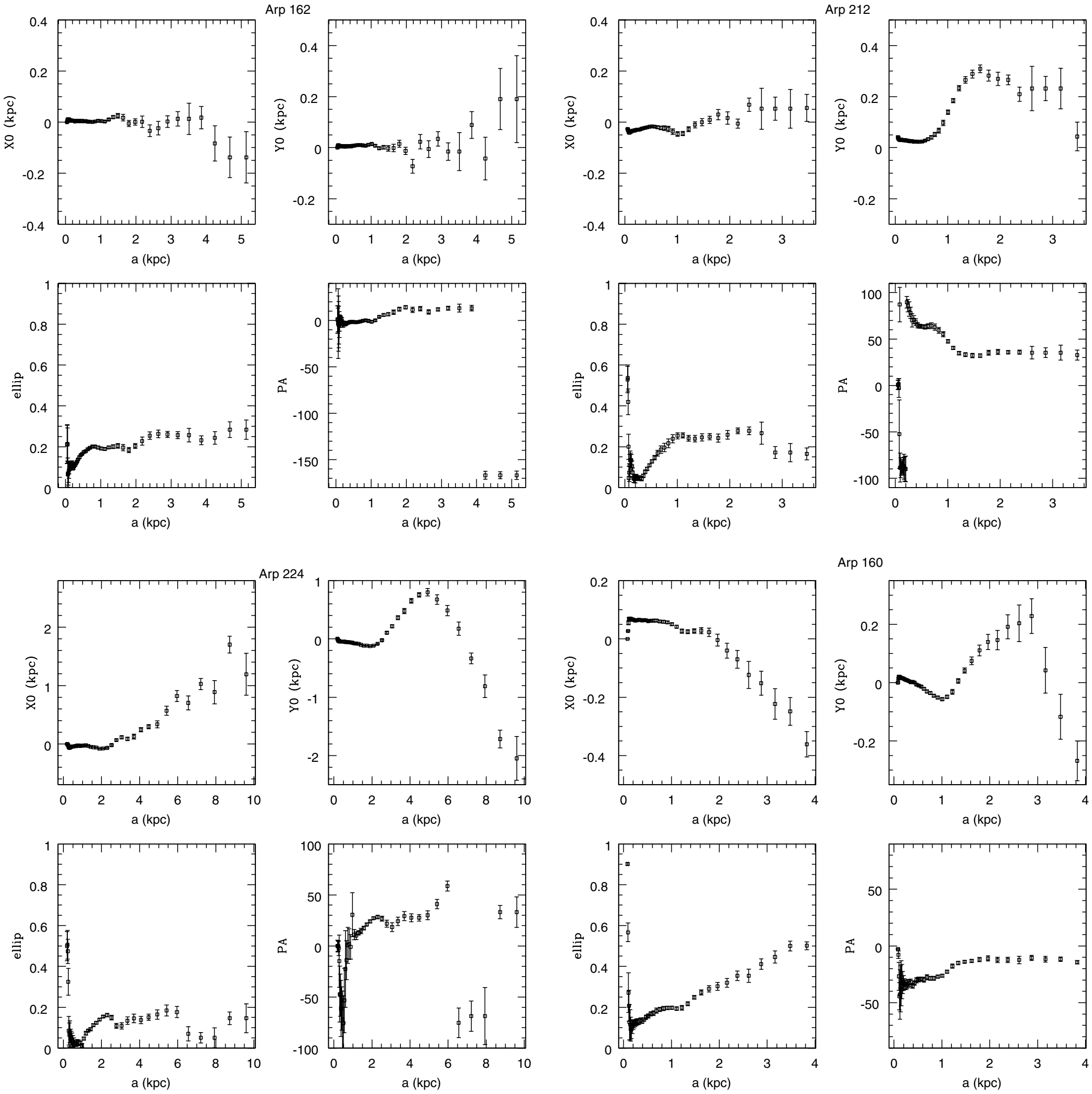

Figure 2 – *continued*

terms of the x- and y-coordinates of the frame, we designated the rest of the image pixels in terms of the distance r and the angle θ from the centre. The image was then cut into annular regions. A polar coordinate grid was centred on the galaxy nucleus with 36 azimuthal bins with 10 degrees per bin, and the number of radial bins depended on the size of the galaxy. In each case, we took the radial width of the annular ring to be at least two times the resolution of the image. The pixel intensity values in each bin were summed to give an average value per bin. Using the task 'NFIT1D' within STSDAS, we fit the following function, f, to each annular region:

$$f = A_0 + A_0[A_1 \cos(x - p_1) + A_2 \cos(2x - 2 \times p_2) + A_3 \cos(3x - 3 \times p_3) + A_4 \cos(4x - 4 \times p_4)], \quad (1)$$

where A_1, A_2, etc. denote the fractional Fourier amplitudes and p_1, p_2, etc. denote the phases of the various Fourier components. Each annular region in the image gives one set of values for the above fitting. The number of points we get in the final plot is the same as the number of annular regions that were made in the original image.

In Fig. 3, we plot the fractional amplitudes A_1, A_2 and the phases p_1, p_2 versus radius r (in arcsec) for $m = 1$ and 2, respectively. The $m = 3$ and 4 amplitudes are generally smaller, and $m = 3$ is important only when $m = 1$ is large. For the sake of brevity, we do not show the amplitudes and phases for $m = 3$ and 4 for the sample. However, in the notes on individual galaxies (Appendix A), we also add comments about A_3 and A_4 when relevant.

Fig. 3 shows that all the mergers studied show a high value of lopsidedness (A_1), the values are generally higher for the class III galaxies–see Table 2 for the detailed values including the averages over the classes. The average values for A_1 and A_2 are given over the central 5 kpc in each merger since it represents a typical central region, and also this allows a comparison between different galaxies.

In order to avoid any spurious variation with class introduced due to the dependence on the band chosen, we have taken homogeneous data (in J band from 2MASS) for all the galaxies for the above non-axisymmetric analysis (Fig. 3), and the K_s-band data from 2MASS for the isophotal analysis (Fig. 2).

Fig. 3 shows that the values of A_2 in mergers are also large. Normally, the values of A_2 are taken to denote bars or spirals or disc ellipticity (Rix & Zaritsky 1995; Bournaud et al. 2005a; Buta et al. 2005). It is hard to see how spiral features can survive the strong disturbance in a merger. We add the evidence from the isophotal

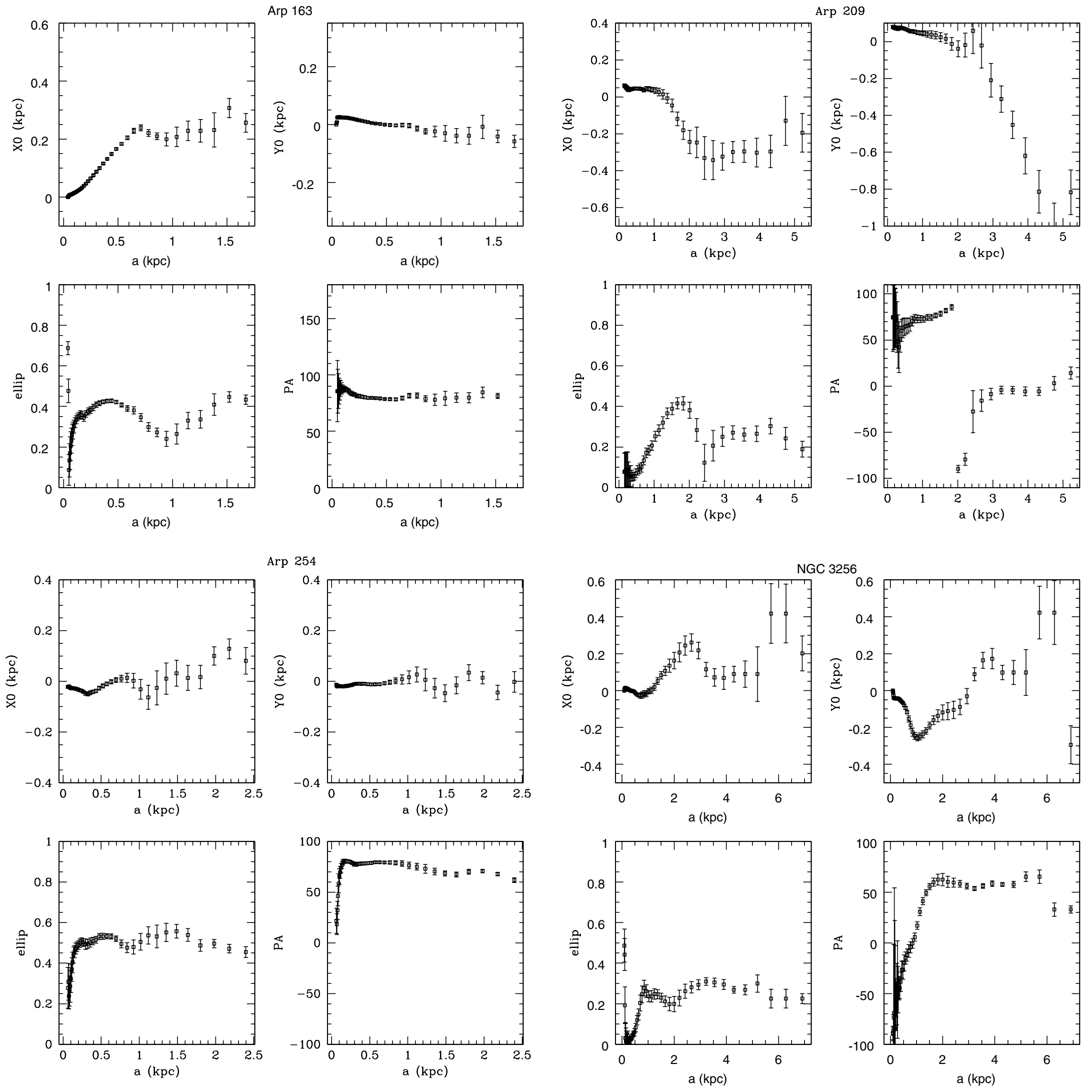

Figure 2 – *continued*

Table 2. Average central asymmetry properties for mergers.

Name	Sloshing of centre (within 1 kpc)	⟨*A*1⟩ (within 5 kpc)	⟨*A*2⟩ (within 5 kpc)
Class I			
Arp 221	0.08	0.16	0.09
Arp 222	0.10	0.04	0.18
Arp 225	0.09	0.03	0.29
AM 0612-373	0.10	0.05	0.17
Avg.: Class I	0.09	0.07	0.18
Class II			
Arp 162	0.06	0.02	0.24
Arp 212	0.08	0.11	0.19
Arp 224	0.14	0.23	0.16
Avg.: Class II	0.09	0.12	0.20
Class III			
Arp 160	0.27	0.15	0.30
Arp 163	0.31	0.15	0.19
Arp 209	0.04	0.23	0.22
Arp 254	0.06	0.09	0.34
AM 1025-433	0.20	0.16	0.29
Avg.: Class III	0.18	0.16	0.27

analysis and find that the characteristic feature of bars, namely increasing ellipticity and a nearly constant PA (e.g. Wozniak et al. 1995) is seen in only three cases, which we conclude have well-defined bars. These are Arp 160, Arp 162 and Arp 163.

Grosbol, Patsis & Pompei (2004) state that a circular disc will appear elliptical when projected and this could give rise to an artificial bisymmetric component with a constant phase. This could be used to explain the high values of A_2 seen in many galaxies in our sample. In fact, this effect is seen in all the galaxies except Arp 221 (class I), Arp 212 (class II) and Arp 209 (class III). Thus, in most cases studied, the merger remnants seem to indicate a preferred disc plane. This is seen even in three of the class I galaxies with an outer elliptical-like profile (Arp 222, Arp 225 and AM0612-373), which is unexpected.

We note, however, that the previous work on deriving the Fourier coefficients to get the asymmetry has been done for spiral galaxies. These galaxies were deprojected by estimating their inclinations assuming that the discs are intrinsically round. It is reasonable to talk about projection effects in the case of spirals and also comparatively easy to deproject these galaxies. However, here we are looking at systems completely or partially distorted by the interaction or a merger and hence it is not possible to estimate the inclination of

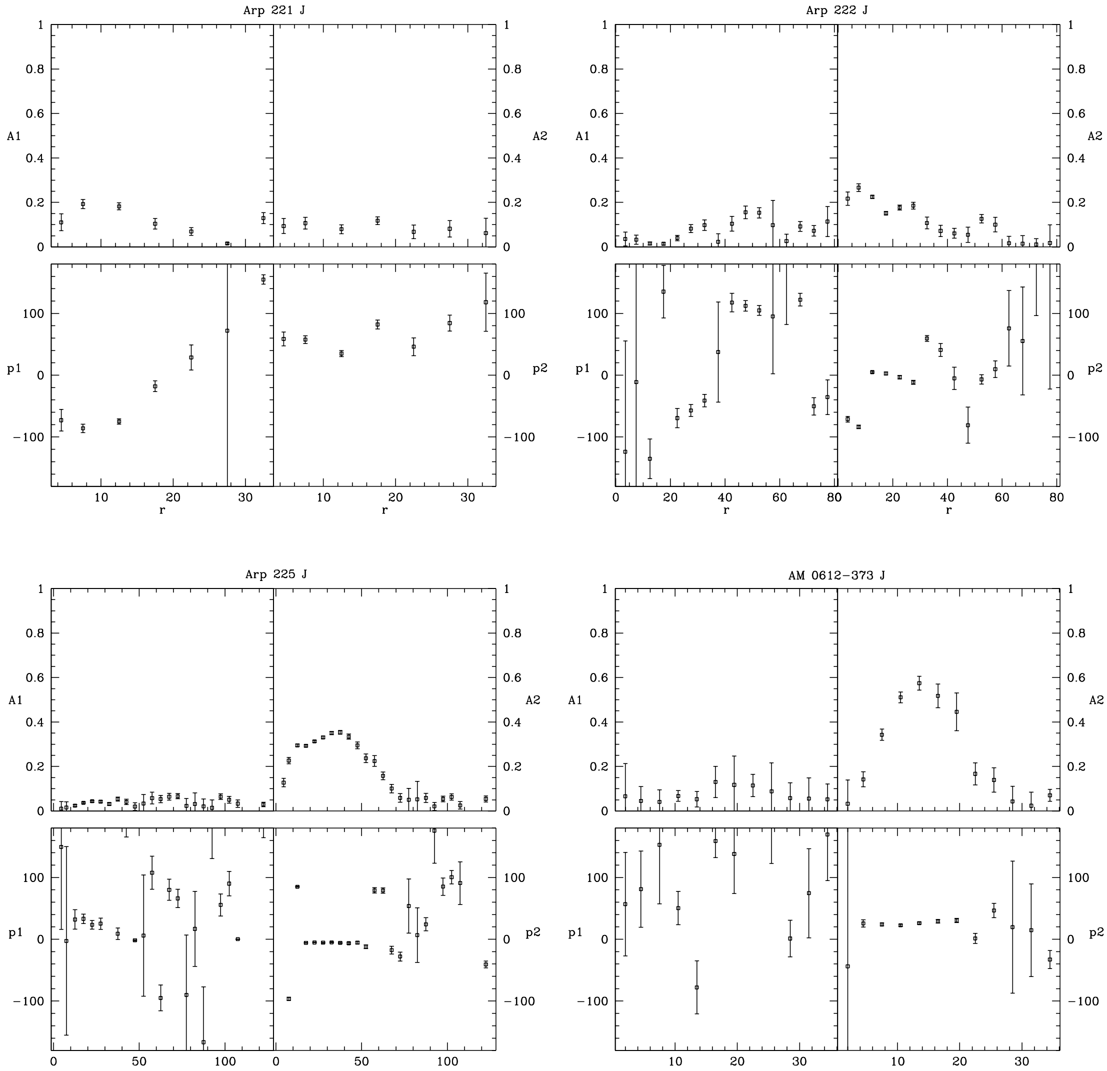

Figure 3. Plots of Fourier amplitudes and phases A_1 and P_1 and A_2 and P_2 versus r, obtained from a non-axisymmetric analysis with a constant centre, for the J-band data for the entire sample studied. All mergers, especially the class III galaxies, show a large amplitude of lopsidedness A_1.

the disc component and correct for inclination effects. A further discussion on the variation of Fourier amplitudes with class types in our sample is given in Section 4.2.

3.3 Comparison with non-merger galaxies

So far we have studied the mergers and we have shown these to have significant central non-axisymmetry. In order to check that the origin of this is related to the merger history, we next carry out a similar analysis for a control sample of non-merging, normal spiral galaxies and show that these indeed have lower central asymmetry.

The selection of a sample of non-merger galaxies is by no means a trivial issue. We do not include any early-type galaxies which are now believed to evolve from late-type galaxies via secular evolution or galaxy mergers. The galaxies selected are nearly face on (for easier analysis), and are late-type and not strongly barred and not active–so as to increase the chance of their having had no interactions in the recent past. The set of eight such normal or non-merger galaxies which are also large enough in angular size to allow the non-axisymmetric analysis in J band (see Section 2) were chosen from the 2MASS Large Galaxy Catalog (Jarrett et al. 2003), and these are NGC 628 (M74), NGC 3147, NGC 4254 (M100), NGC 4321 (M99), NGC 4540, NGC 4689, NGC 5248, NGC 5377.

These show an outer exponential fit as expected for normal spiral galaxies. The basic data for these, including the derived disc scalelength ($R_{\rm D}$), is listed in Table 3.

The isophotal analysis for the $K_{\rm s}$-band data (as in Section 3.1) and the Fourier analysis for the J-band data (as in Section 3.2) were carried out for this sample. The resulting values of sloshing within 1 kpc and the mean A_1 and A_2 within 5 kpc are given in Table 4. We find that these show a lower magnitude for the sloshing of isophotes and a lower mean central A_1 value (compare with Table 2). The non-merger or normal galaxies show sloshing values which are smaller by a factor of 2 compared to the unrelaxed (or class III) mergers. The Fourier amplitudes for lopsidedness for the normal galaxies are smaller by a factor of 2–3 compared to classes I and II remnants and smaller by a factor of 4 compared to the class III remnants. Thus, the origin for the high central asymmetry (especially A_1) observed in the merger remnants can be attributed to its merger history.

Interestingly, the mean A_2 value for this sample is comparable to the classes I and II galaxies, thus providing additional support for our interpretation of this (Section 3.2) as being due to an inclined disc.

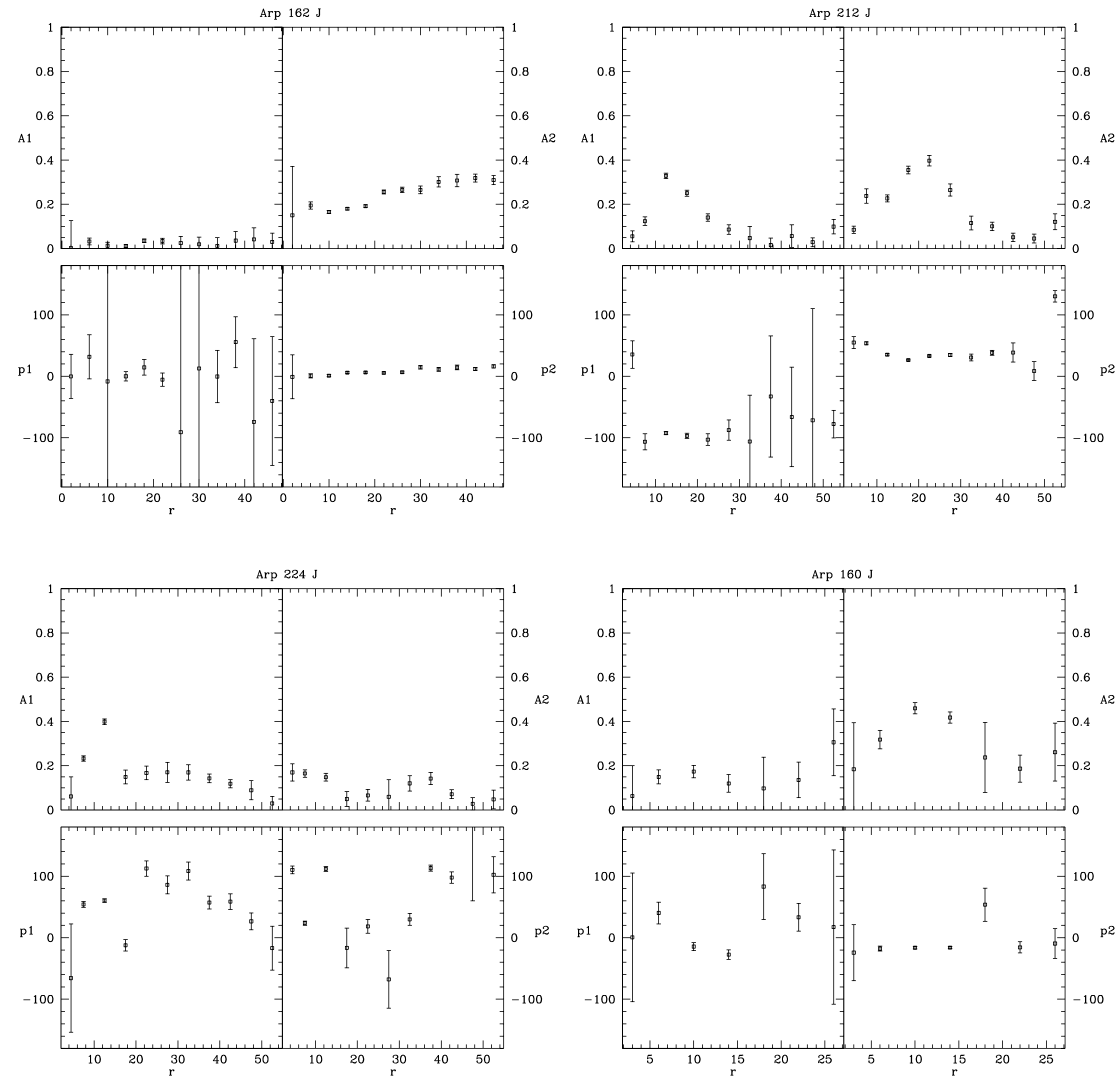

Figure 3 – *continued*

The higher values for A_2 in the unrelaxed (class III) type galaxies then could be due to a thicker disc seen at an angle.

4 DYNAMICAL IMPLICATIONS

4.1 Long-lived central asymmetry

The one clear result from this work is that all mergers show high levels of asymmetry in their central few kpc regions, even in systems that have relaxed in the outer parts. The large sample of galaxies used here gives a statistical idea of the *in situ* non-axisymmetry in merger remnants with a variety of dynamical properties. *N*-body simulations of unequal-mass mergers by Bournaud et al. (2004) have shown that the advanced remnants with signs of tidal interactions and disturbed profiles in the outer regions (beyond say 20 kpc or so) have ages $\leqslant$2 Gyr. Classes I and II represent mergers of different mass ratios of masses 1:1–3:1 and 4.5–10:1, respectively (Bournaud et al. 2005b), while class III could be younger remnants ($\sim$1 Gyr). The dynamical time-scale in the central few kpc, where the random motions are a few hundred km s^{-1} (e.g. Jog & Chitre 2002), is $\sim$10^7 yr. Thus, the central regions in mergers are not relaxed in over a few hundred local dynamical time-scales. This is an important and a robust dynamical result, and has important implications for the evolution of the very central regions of mergers.

For example, such asymmetries could play an important role in the fuelling of the central black hole in an active galactic nucleus since they provide a means of outward transfer of angular momentum. The central asymmetries can help fuel a central black hole for a long time $\sim$100 dynamical time-scales. Also, these can be important in the gradual build-up of bulges–on lines of bars as an intermediate stage in the build-up of boxy bulges by mergers (see e.g. Walker, Mihos & Hernquist 1996).

It is instructive to compare the central lopsidedness in mergers with the lopsidedness in the outer discs of normal isolated spiral galaxies. The latter was initially believed to be short lived ($<$1 Gyr) and to get wound up in a few dynamical time-scales (Baldwin, Lynden-Bell & Sancisi 1980). However, more recent *N*-body studies of evolution of disc lopsidedness have shown that these features can be surprisingly long-lived to more than 2 Gyr or several tens of disc dynamical time-scales, although the physical reason for this is still not understood (Bournaud et al. 2005a). The results from the present paper confirm the asymmetry in the central

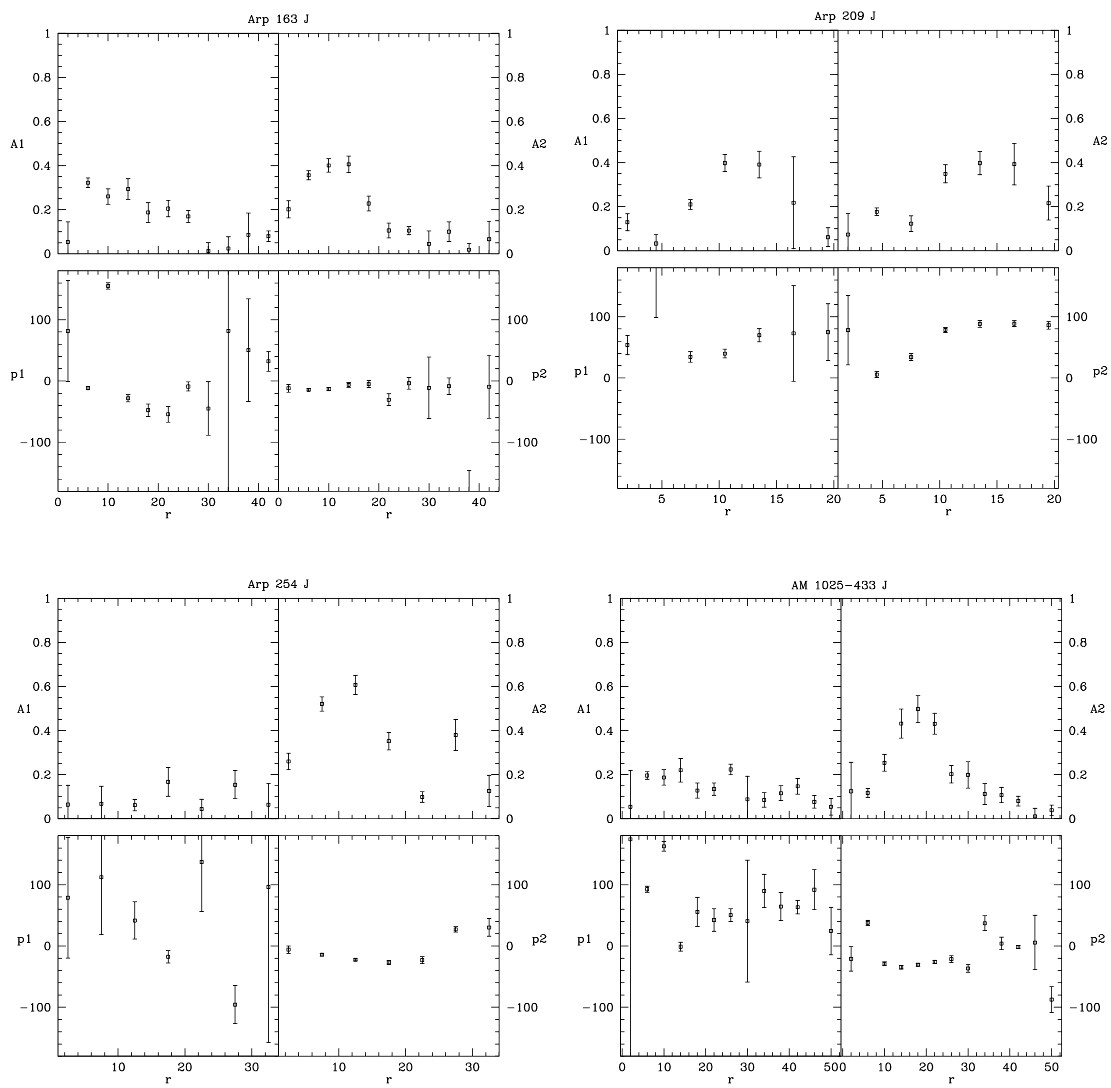

Figure 3 – *continued*

regions to be also long lived and the ratio of its lifetime to the local dynamical time-scales is even higher ∼100.

It should be noted that central regions of normal galaxies, such as our Galaxy, M 31 and M 33, also show sloshing (Miller & Smith 1992; also see Section 3.2), where the centre is off-set with respect to the outer isophotes but the other isophotes are concentric and the off-set is believed to be due to overstability, whereas in the mergers we have studied the isophotes are steadily off-centred with respect to each other. Thus, the origin and evolution of central asymmetry could be different in these cases, which is not surprising given the totally different systems being studied.

4.2 Lopsidedness and bars in mergers

(i) *Lopsidedness in centres of mergers*. The amplitude of $m = 1$ indicates lopsidedness and is not affected by inclination effects (e.g. Rix & Zaritsky 1995). This is particularly important in the study of mergers, where the disc plane may not be so well defined in the central regions.

We note that the physical parameters, A_1, the amplitude and p_1, the phase of lopsidedness, show a different behaviour in mergers than that in the outer parts of normal galaxies. In the centres of mergers, the amplitude A_1 peaks at an intermediate radius of a few kpc and then decreases at larger radii (see Fig. 3), and the phase p_1 shows large fluctuations with radius–see for example the results for Arp 221, Arp 224 and Arp 163 in Table 3. In contrast, in the outer parts (beyond ∼1.5 disc scalelengths or ∼5 kpc) of normal galaxies the A_1 values show a steady increase with radius, and the phase p_1 is nearly constant with radius–as seen from Rix & Zaritsky (1995) and Angiras et al. (2006). This constancy in phase indicates a global distortion (Jog 1997). Thus, these two features clearly point to a different physical origin and evolution of lopsidedness in centres of mergers.

Our sample is chosen so that the two nuclei have coalesced to <2 arcsec or the resolution of the data, or an average separation of <500 pc (see Table 2). The dynamical evolution of the central regions of mergers including the long lifetime of the central lopsidedness needs to be studied theoretically.

(ii) *Interpretation of A_2 values*. The high values of A_2 measured in the merger remnants here is unexpected, since a merger is expected to result in the disruption of a bar (Pfenniger 1991; Athanassoula & Bosma 2003). Also, these bars are stronger compared to the bars in normal galaxies (compare Table 2 of this paper with the appendix in Bournaud et al. 2005a).

Table 3. Basic data on normal galaxies.

Name	Alt. name	R_D (kpc)
NGC 628	M74	2.51 ± 0.13
NGC 3147	–	3.82 ± 0.09
NGC 4254	M100	9.48 ± 0.75
NGC 4321	M99	3.81 ± 0.27
NGC 4540	–	1.37 ± 0.04
NGC 4689	–	4.39 ± 0.32
NGC 5248	–	7.34 ± 1.79
NGC 5377	–	3.70 ± 0.21

Table 4. Average central asymmetry for normal galaxies.

Name	Sloshing of centre (within 1 kpc)	⟨A1⟩ (within 5 kpc)	⟨A2⟩ (within 5 kpc)
NGC 628	0.07	0.04	0.10
NGC 3147	0.07	0.03	0.08
NGC 4254	0.09	0.02	0.14
NGC 4321	0.02	0.03	0.15
NGC 4540	0.13	0.10	0.15
NGC 4689	0.10	0.06	0.10
NGC 5248	0.06	0.07	0.34
NGC 5377	0.04	0.02	0.53
Average:	0.07	0.04	0.20

It is interesting that in two of our sample galaxies which show a bar (Arp 160 and Arp 163), the outer regions are not relaxed and hence cannot be fit by either an $r^{1/4}$ or an exponential profile, and yet the central region shows a strong bar and lopsidedness. Thus, the orbit building for the bars seems to proceed irrespective of the outer disturbed regions. The other galaxy showing a bar, Arp 162, is a class II galaxy which has a relaxed, exponential outer profile.

The high values of A_2 measured in the other, non-barred galaxies could be due to an inclined thick disc, as discussed in Section 3.2. The class II galaxies are hybrid systems with high random velocities and thick discs (Jog & Chitre 2002) and these have been shown to arise naturally in mergers of unequal-mass galaxies covering a range of 4.5:1–10:1 (Bournaud et al. 2004). The high values of A_2 seen in the sample mergers of class II can thus be naturally explained as arising due to an inclined thick disc.

The values of A_2 measured are higher for all class III galaxies. The high values of A_2 if taken as an indication of an inclined thick disc in no-fit galaxies, which do not have a bar (such as Arp 254 and AM 1025-433), indicate the existence of a galactic plane even if the outer regions are highly disturbed.

The high A_2 values seen in class I galaxies with elliptical-like profiles is even more surprising. The isophotal analysis shows that these do not show the pattern expected of a bar, and we have argued that this could be due to an inclined disc (Section 3.2), thus these seem to be unusual systems.

In any case, it is clear that the central asymmetries ($m = 1$ and $m = 2$) seen in class I remnants indicate that they are dynamically still far from being regular elliptical galaxies. This is extra evidence in addition to the other arguments such as the high gas content, extended tails and outer disturbed profiles, and different kinematics seen in mergers which have been used to show that merger remnants and ellipticals are not identical (e.g. Kormendy & Sanders 1992; Shier & Fischer 1998).

(iii) *Variation with mass ratios and epoch of mergers.* There is no discernible difference in the sloshing values or the A_2 values for classes I and II (see Table 2), while the A_1 values are higher for class II galaxies. Thus, the mass ratio of the progenitor or merging galaxies does not seem to significantly affect the degree of central non-axisymmetry in mergers at a later stage in its evolution, when the outer parts have relaxed into an elliptical-like (class I) or an exponential (class II) luminosity profile.

However, the stage of relaxation does seem to be a significant factor because the class III galaxies, which are in early stages of relaxation, do show higher amplitudes of sloshing and lopsidedness. The various galaxies can thus be arranged in a time sequence for variation of central asymmetry as follows; the normal or non-merger galaxies (lowest asymmetry), young merger remnants of <1 Gyr or class III mergers (highest asymmetry), evolved merger remnants of <2 Gyr with relaxed outer regions or class I and II mergers (higher asymmetry compared to normal galaxies but lower compared to the young remnants). The dynamical evolution of the non-axisymmetric amplitude and its relation to the relaxation of the outer regions need to be studied by future N-body simulations.

4.3 Sloshing values and Fourier amplitudes

While both sloshing and the Fourier amplitudes represent asymmetry, they do not represent the same physical quantity. For example, a galaxy which has concentric isophotes and hence shows no sloshing could still have a non-axisymmetric mass distribution as in a bar or a spiral arm ($m = 2$). Thus, the sloshing represents odd values of non-axisymmetric Fourier amplitudes. Indeed, the typical sloshing and A_1 values (see Figs 2 and 3, or Table 2) are correlated–although it must be kept in mind that the sloshing represents only the inner regions (<1 kpc) of a galaxy while the non-axisymmetric analysis is typically carried out over a larger radial range of up to 5 kpc or more.

On comparing with the values for the normal galaxies (Tables 2 and 4), we find that these have comparable values for sloshing (especially the classes I and II mergers, and the normal galaxies sample), but the A_1 values for the mergers are distinctly higher than for the normal galaxies.

5 SUMMARY

We have measured the non-axisymmetry in the mass distribution within the central few kpc of advanced mergers of galaxies which have merged into a single nucleus but have indications of interactions including tidal tails. The main results obtained are as follows.

(i) The mergers show strong non-axisymmetry–with the centres of isophotes showing a sloshing by ∼20–30 per cent within the central 1 kpc. The asymmetry is also high, as measured by the Fourier amplitudes of the central light distribution. The typical fractional lopsided amplitude (A_1) within the central 5 kpc is found to be high ∼0.12 going up to 0.2, while the typical A_2 values are higher ∼0.2 going up to 0.3. This implies the presence of bars as in Arp 160, Arp 162 and Arp 163 or thick discs as in the rest of the sample, both of which are unexpected in mergers with elliptical profiles or in no-fit, unrelaxed galaxies.

The corresponding values, especially for the lopsidedness for a control sample of non-merger galaxies, are smaller by a factor of 2–4; this confirms that the high central asymmetry in mergers discovered and measured in this paper can be truly attributed to the merger history.

(ii) The ratio of masses of galaxies undergoing the merger does not have a strong influence on the value of the central asymmetry once the outer regions have relaxed (Sections 1 and 4.2).

(iii) The stage of merger, however, does seem to be significant because the galaxies, where the outer regions are non-relaxed, show a higher amplitude of asymmetry in the inner regions (Section 4.2).

(iv) The mergers are about 1–2 Gyr old as shown by the N-body simulations (Bournaud et al. 2004). Thus, in all cases studied, the central asymmetry appears to be long lived, lasting for over 100 local dynamical time-scales. This can be important for the dynamical evolution of the central regions of mergers.

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APPENDIX A: NOTES ON INDIVIDUAL GALAXIES

The details of sloshing as well as the non-axisymmetric Fourier amplitudes obtained for each galaxy in Section 3 are summarized below.

Class I galaxies

(i) Arp 221. The coordinates of the centre remain constant in the inner 4 arcsec and change beyond that. The non-axisymmetric analysis shows that the A_2, A_3 and A_4 values are small while A_1 shows a maximum of 0.25 at 8 arcsec.

(ii) Arp 222. The coordinates of the centre remain constant in the inner 20 arcsec and change beyond that. This galaxy has very low A_1 values. A_2 maintains a constant value of 0.3 from the centre to about 30 arcsec. The A_3 and A_4 values are both very small.

(iii) Arp 225. The coordinates of the centre are constant in the inner 18 arcsec. This galaxy shows low values of A_1, A_3 and A_4 but high A_2 values. The behaviour of A_2 is similar to that seen in Arp 222. A_2 maintains a value of 0.3 in the inner 45 arcsec.

(iv) AM 0612-373. There is no substantial change in the coordinates of the centre, with a total change of 1 pixel for $x0$ and $y0$. The value of A_1 is low, while A_2 is quite high, peaking at 0.6 at 15 arcsec. The A_3 and A_4 values are fairly high.

Class II galaxies

(v) Arp 162. The centre coordinates $x0$ and $y0$ are constant in the inner 14 arcsec. The values of A_1 and A_3 are extremely small. The amplitude A_2 starts off at about 0.2 between 6 and 20 arcsec and then increases to 0.3 beyond that, while A_4 is low in the inner 20 arcsec and then increases. The phase angle is nearly constant throughout for the $m = 2$ and 4 components.

(vi) Arp 212. The centre coordinates $x0$ and $y0$ remain constant in the inner 6 arcsec and then change substantially. All A coefficients show (nearly) double-peaked behaviour. The values of the A coefficients decrease in the order $A_1 > A_2 > A_3 > A_4$.

(vii) Arp 224. The centre ($x0$, $y0$) remains constant in the inner 6 arcsec. The value of A_1 is high showing a peak of 0.3 at 12 arcsec. In this case, also $A_1 > A_2 > A_3 > A_4$.

Class III galaxies

(viii) Arp 160. This shows a constantly changing centre ($x0$, $y0$) for the subsequent isophotes. The values of A_2 are also high with a peak of 0.45 at 10 arcsec.

(ix) Arp 163. This also shows a constantly changing centre ($x0$, $y0$) for the nearby isophotes. The value of the $m = 2$ amplitude A_2 is the strongest, with a maximum of 0.4 between 10 and 14 arcsec. The value of A_1 peaks at 0.3 at 6 arcsec and A_4 peaks at 0.3 at 14 arcsec. The value of A_3 is small at all radii.

(x) Arp 209. The centre coordinates are constant in the inner 4 arcsec and vary thereafter. The values of A_1, A_2 and A_3 are high.

(xi) Arp 254. This shows changing coordinates for the centre. The values of A_2 and A_4 are large as compared to the values of A_1 and A_3.

(xii) AM 1045-433. This is a Toomre sequence galaxy. Here, the coordinates of the centre ($x0$, $y0$) show a change from the innermost region itself. The value of A_2 is high with a peak value of 0.5 at 20 arcsec. This galaxy shows the following values for the Fourier amplitudes $A_2 > A_3 > A_4 > A_1$.

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