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Letter to the Editor

Spiral-like light profiles but elliptical-like kinematics in mergers of galaxies

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Abstract. It is commonly accepted that a merger of two spiral galaxies results in a remnant with an elliptical-like surface-brightness profile. Surprisingly, our recent study (Chitre & Jog 2002) of the 2MASS data for twenty-seven advanced mergers of galaxies has shown that half of these have a light distribution that decreases exponentially with radius. Such a distribution normally characterizes a rotationally supported disk in a spiral galaxy. Here we show from kinematic data for two of these mergers, Arp 224 and Arp 214, that the main support against gravitational collapse comes from pressure due to random motion of stars as seen in an elliptical galaxy rather than from rotation. The origin of the unusual combination of properties seen here is a puzzle. The standard theoretical *N*-body models in the literature cannot account for these systems. Further observational and dynamical studies of this new class of merger remnants are needed, and would be important for understanding merger dynamics and galaxy evolution.

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

1. Introduction

It is well-established observationally that a merger of two gas-rich spirals can result in an $r^{1/4}$ de Vaucouleurs radial profile typical of ellipticals (Schweizer 1982; Wright et al. 1990; Stanford & Bushouse 1991). Our recent study (Chitre & Jog 2002) has shown the existence of robust, exponential profiles in surface brightness in thirteen advanced mergers of spiral galaxies, similar to the radial profiles seen in isolated spiral galaxies (Freeman 1970). This result is unexpected and is in contrast to the result from the earlier studies of mergers (Wright et al. 1990; Scoville et al. 2000; Genzel et al. 2001). We note that these earlier studies had mainly concentrated on infrared-bright galaxies whereas our sample was selected purely based on a disturbed appearance without any bias towards IR luminosity. The existence of exponential profiles, that too in a large fraction of the sample, is a puzzle and needs further dynamical study.

To get a coherent picture of the mergers with exponential profiles, in this Letter, we study the complementary information from kinematics available for two of these galaxies, namely Arp 224 (NGC 3921) and Arp 214 (NGC 3718). We also obtain additional photometric properties of the thirteen galaxies with exponential profiles by analyzing the K_s band images from the Two Micron All Sky Survey (2MASS). The most significant result from this paper is that these merger remnants appear to be largely pressure-supported as seen in an elliptical galaxy and yet show an exponential mass profile as seen in a spiral galaxy.

Section 2 gives the kinematic data for the above two galaxies and the results deduced, and also the photometric properties of the entire sample. Section 3 gives the dynamical implications and puzzles from these results, and Sect. 4 contains a summary and discussion.

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2. Results on photometric and kinematic properties

The kinematical data on rotation and random motion for Arp 224 and Arp 214 are taken from the HYPERCAT archival database (Simien & Prugniel 1997; Heraudeau & Simien 1998). These observations involve absorption spectroscopic measurements and a Fourier-fitting analysis and give the rotation velocity projected along the major axis and the velocity dispersion around it with an accuracy of dispersion of <30 km s^{-1}.

Figures 1 and 2 show the variation in the surface brightness (μ_K), the circular rotation velocity (V_c), and the velocity dispersion (σ), with radius for Arp 224 and Arp 214 respectively. The surface brightness profile was derived from the 2MASS data (Figs. 1a and 2a) and it shows a robust exponential fit (see Chitre & Jog 2002 for details). On doing a similar fitting for the J and the H band data from 2MASS, we get disk scale-lengths that are comparable within the error bars (of ≤10%), with no clear dependence on wavelength. Thus, the luminosity profile is not affected significantly by the dust extinction within the two galaxies.

The most striking result from Figs. 1c and 2c is that the velocity dispersion values are large ~100 km s^{-1} within a few kpc of the galaxy centre. Thus, these merger remnants are largely pressure-dominated as seen in an elliptical galaxy and yet surprisingly show an exponential mass profile as seen in an isolated spiral galaxy. Given the high velocity dispersion values, the mass distribution is probably not confined to a thin disk.

There are, however, subtle differences between the kinematics of these two galaxies and a typical elliptical galaxy. First, in the two galaxies studied here, the values of both the rotation velocity and the velocity dispersion are high, but the dispersion is generally larger ($V_c \leq \sigma$) – compare Figs. 1b and c, and Figs. 2b and c. Thus, the support against gravitational collapse due to both pressure and rotation is important though the pressure-support dominates over a large radial range. In a typical bright giant elliptical, on the other hand, the values of rotation velocity seen are much smaller ~few × 10 km s^{-1} (Binney & Merrifield 1998), thus the support due to rotation is negligible. The kinematics of the two galaxies studied here is also in a stark contrast to a typical spiral disk which is supported by rotation.

Second, the velocity dispersion increases monotonically with radius in the outer parts in both Arp 224 and Arp 214, unlike in a typical elliptical galaxy (Binney & Merrifield 1998). This is probably a sign of its tidal origin and it also points to the existence of an outer, perhaps unrelaxed component which shows the exponential mass profile. We obtained the ellipticity of the isophotal contours from the K_s band images for these galaxies. Interestingly, we find that in both cases, the ellipticity shows a sharp discontinuity at the region where the velocity dispersion begins to rise again, at ~10″ (on the positive side of the major axis) for Arp 224 and at ~20″ (on both the sides) for Arp 214. This is also the region beyond which the exponential disk gives a good fit (see Figs. 1a and 2a). The ellipticity drops from a maximum of 0.18 at 14″ to 0.07 at 17″ in Arp 224, while it drops from a maximum of 0.14 at 19″ to 0.05 at 21″ in Arp 214. This gives an independent confirmation of a separate structural component (a disk) in the outer parts of the galaxy, outside of the central bulge. Note that this is approximately the radius at which the rotation curve shows a maximum. The coincidence of the rise in the velocity dispersion and the fall in the rotation curve in both these cases can be understood physically as arising due to the phenomenon of asymmetric drift (Binney & Tremaine 1987). This aspect will be studied in a future paper.

We note that in detail the kinematics show a complex behaviour. For example, the rotation curve is asymmetric on the two sides of the major axis for Arp 224 (Fig. 1b). This is probably due to the strong disturbance that the galaxy has undergone, and is not surprising. Note that even normal galaxies show a significant rotational asymmetry of a lopsided nature, representing the effects of a past tidal encounter (Jog 2002).

In Arp 214, the HI gas shows disturbed kinematics believed to be due to a projection of the outer warped and twisted disk onto the inner regions (Schwarz 1985). This model can be ruled out for the stellar kinematics since the latter spatially cover a

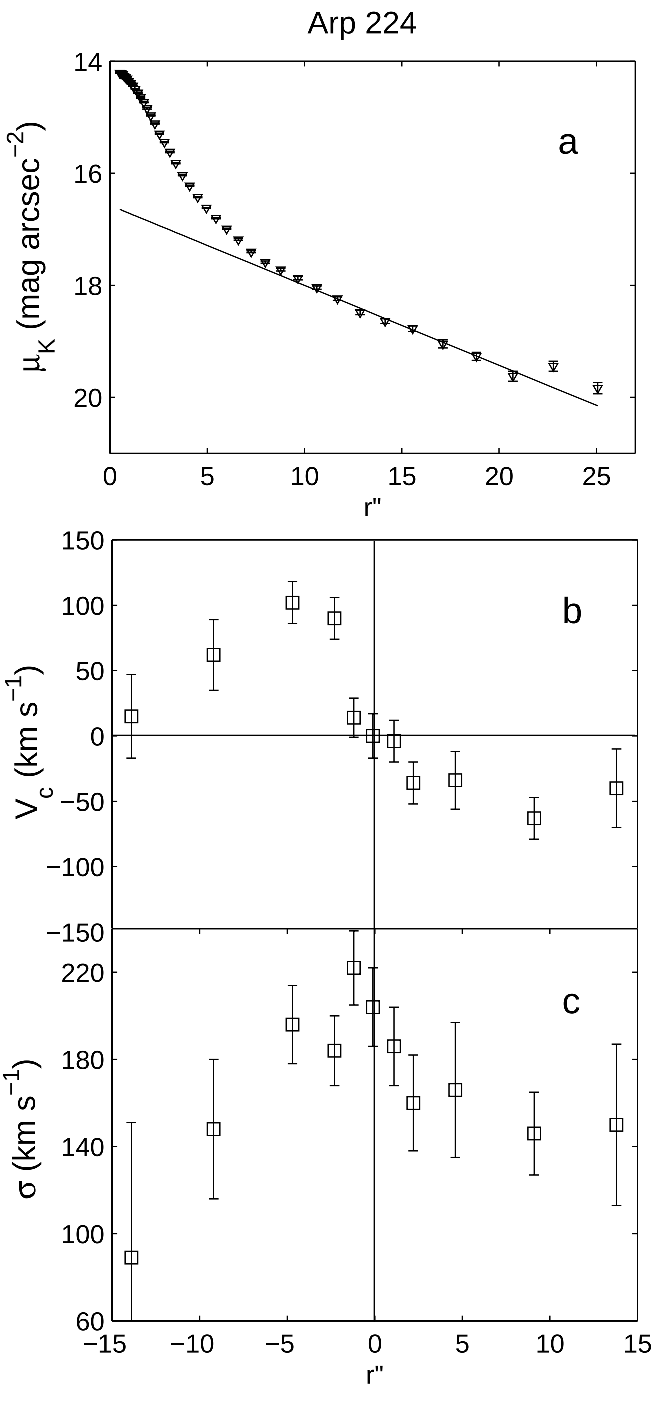

Fig. 1. Photometric **a)** and kinematic (**b)** and **c)**) properties of Arp 224. **a)** shows the surface brightness distribution with radius in the K_s band derived using the image from the 2MASS data. The inverted triangles denote the observed values and the straight line is obtained by fitting an exponential to the outer points. The exponential disk gives a good fit beyond 10″ (where 1″ = 0.38 kpc). The disk scalelength is 7.6″ or 2.91 kpc. **b)** shows V_c, the circular rotation velocity of Arp 224 on either side of the galaxy centre. The rotation velocity reaches a maximum value at around 10″ and then decreases beyond this radius. **c)** shows σ, the velocity dispersion. It peaks at the centre with a value of ~210 km s^{-1} and then dips gradually upto ~10″ on either side, and again increases beyond this radius on the positive side of the axis. V_c is less than σ at all radii covered by the kinematical data.

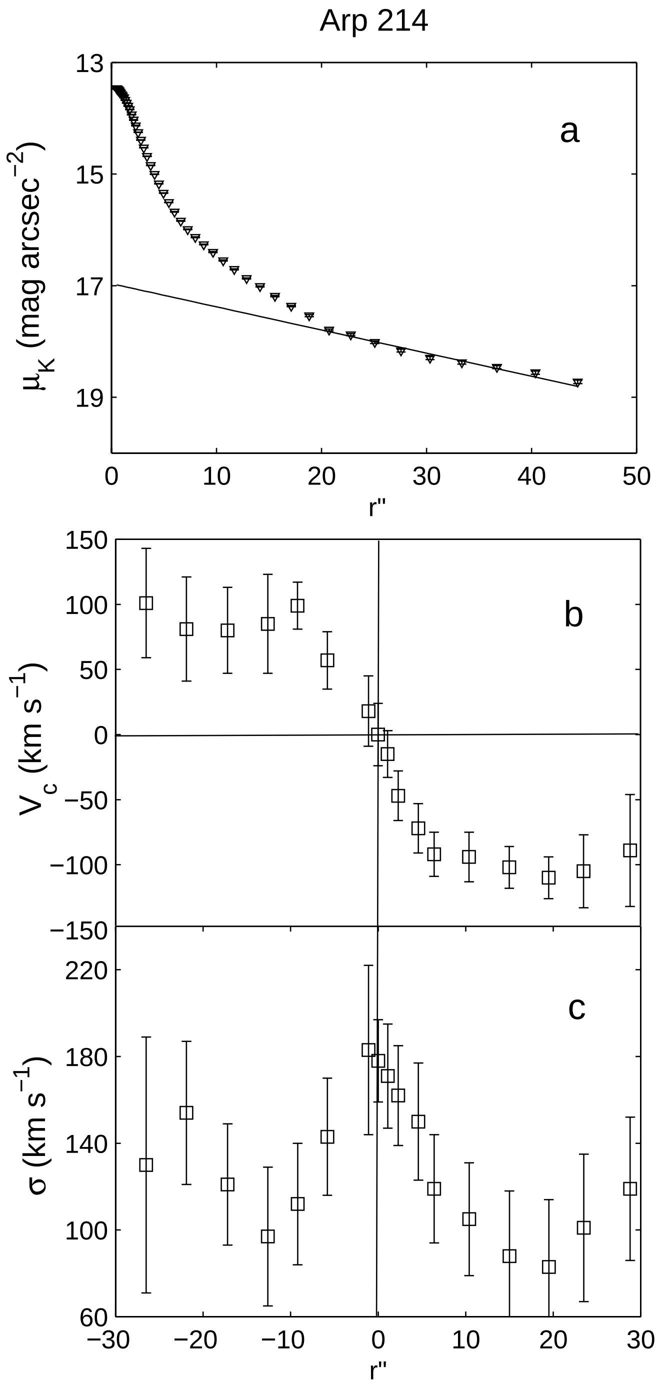

Fig. 2. Photometric **a)** and kinematic (**b)** and **c)**) properties of Arp 214, with details similar to Fig. 1. **a)** The exponential disk gives a good fit beyond 20″ (where 1″ = 0.065 kpc). The disk scalelength is 26.5″ or 1.72 kpc. **b)** V_c, the rotation velocity reaches a maximum value at 20″ and then decreases beyond this radius. **c)** σ, the velocity dispersion peaks at the centre with a value of $\sim$180 km s^{-1} and falls on either side, and again increases beyond about 20″. Between 10″–20″, V_c is larger than σ, beyond 20″ the dispersion dominates over rotation again.

central region even smaller than the beam-size of the HI study. Also, the gas and stars are often decoupled in mergers (Genzel et al. 2001), mainly because of the dissipational nature of gas. In Arp 224, any incoming tails (Hibbard & Mihos 1995), if aligned along the line-of-sight, could give rise to a spurious dispersion but it would need a contrived geometry for this scenario to explain the details of the dispersion profile observed. Thus, both these alternatives for the origin of the high velocity dispersion (σ) observed can be ruled out.

Further, the symmetric central profile of σ (as in an elliptical), the increase in σ with radius in the outer parts where the exponential disk fits well, and the correlation between the falling rotation curve and the increasing σ, convincingly show that the values of σ observed in Figs. 1c and 2c represent true stellar random motion, and are an intrinsic property of the galaxy. Thus, our interpretation of these systems as being mainly pressure-supported is well-justified.

So far for simplicity we have portrayed spiral and elliptical galaxies as being supported respectively by rotation and random motion alone. In reality both types can sometimes show a range of dynamical and photometric properties. For example, the low-luminosity ellipticals are often disky (Faber et al. 1997), and show a significant rotational support with V_c/σ between 0.5–1.0 (Bender et al. 1992), and can show exponential luminosity profiles (Caon et al. 1993). On the other hand, bulges in isolated spiral galaxies are dynamically hot (Binney & Merrifield 1998), and sometimes show a comparable support from both rotation and random motion (Bender et al. 1992). This behaviour is not understood, and the present study on mergers may help shed some light on this.

In order to better understand the mass distribution and evolution of the thirteen mergers showing exponential profiles (Chitre & Jog 2002), we compare their photometric properties with those of typical isolated spirals. We find that the distribution of the K_s band disk scalelengths of these is similar to that for a sample of undisturbed spiral galaxies (Peletier et al. 1994). Such a similarity was noted earlier (Schwarzkopf & Dettmar 2000), but only for a merger of galaxies with a mass ratio less than 1:10. Next, a simultaneous disk plus an $r^{1/4}$ profile for the bulge was tried, but this overestimates the luminosity in the middle radial range, and hence is not a good fit for any of the thirteen galaxies. A Sersic or a generalized de Vaucouleurs fit with an $r^{1/n}$ profile (e.g., Caon et al. 1993) was also attempted, but the resulting value of n is extremely sensitive to the radial range chosen, hence this fit cannot be used. The disk scalelengths for our sample galaxies are comparable to those for isolated spirals as shown above, hence these are too large compared to those of typical S0 galaxies (Binney & Tremaine 1987).

It is interesting that the disky ellipticals show (Scorza & Bender 1995) smaller scalelengths than S0's or Sa's while our sample shows values similar to normal spirals, implying different dynamical evolution of the disky ellipticals compared to our sample. The idea of a different origin is also supported by the dynamical data presented here, because Arp 224 and Arp 214 are mainly pressure-supported whereas the low-luminosity, disky ellipticals studied by Rix et al. (1999) show a dominant rotational support beyond one effective radius. Another difference is that the Rix et al. (1999) sample galaxies are less luminous than $M_B = -19.5$, whereas our galaxies are brighter than this.

3. Dynamical implications and puzzles

The results in Sect. 2 show that despite the evidence for a strong tidal interaction such as the high velocity dispersion, tidal tails, and a disturbed appearance as shown by these galaxies, their radial mass distribution seems largely unaffected. However, because of the high velocity dispersion, the disk is probably puffed up vertically, and also would not show large-scale spiral structure (Binney & Tremaine 1987). Our work shows that the galaxy disks are not fragile as is sometimes suggested from their vertical heating during an encounter (Toth & Ostriker 1992), in fact if anything the galaxies are robust in their radial mass distribution.

These mergers seem to have avoided suffering a complete violent relaxation (Barnes 1992) that would have resulted in an $r^{1/4}$ de Vaucouleurs type of profile (de Vaucouleurs 1977) as seen in an elliptical galaxy. Yet these galaxies are indistinguishable (Chitre & Jog 2002) in appearance from the mergers which show an $r^{1/4}$ profile. Thus the origin of these galaxies and their dynamics is a puzzle. The standard indicators of a galaxy type, namely the radial mass distribution and the kinematics, do not tally in these galaxies. This may indicate that these galaxies are in transition from a spiral galaxy to an early-type spheroidal system, and hence have properties interim to both of these types.

We suggest that future observations that give kinematic data for the other eleven mergers with the exponential profiles would be extremely useful. This will help establish this new class of mergers on a firmer footing.

How do these mergers compare with the theoretical models? The theoretical work involving N-body simulations of mergers of galaxies has a vast range of parameter space available covering different progenitor mass ratios, encounter geometry, and inclination of galaxies, all of which has not yet been fully sampled. We find that there are no analogs of such pressure-supported remnants with exponential profiles in the models in the literature so far. Mergers of galaxies with equal mass (Barnes 1992), and comparable masses with a mass ratio in the range of 1:4–1:1 (Naab & Burkert 2001; Bendo & Barnes 2000), have been studied. These result in a pressure-supported remnant, with an $r^{1/4}$ profile, as seen in a bright giant elliptical galaxy – and different from our sample (Sect. 2). These models were largely motivated by the observations of ultraluminous galaxies, which involve mergers of comparable-mass galaxies. However, the models with the mass ratios 1:4 and 1:3 cannot yet be excluded, because for some input parameters these produce remnants with properties overlapping with those observed for Arp 224 and Arp 214. First, these remnants can have comparable support from rotation and random motion, with $V_c/\sigma \sim 0.5{-}1$ at one effective radius (Naab et al. 1999; Naab & Burkert 2001; Cretton et al. 2001; Barnes 1998). This range is roughly comparable to the observed data presented in our work. Second, the unpublished surface density results for the models of Naab & Burkert (Naab 2002, personal communication) show a trend to more disk-like profiles in the outer regions.

At the other end of the mass ratio, the studies of a satellite merging with a parent galaxy with a mass ratio of about 1:10 (Quinn et al. 1993; Walker et al. 1996; Velazquez & White 1999) show an increase in the random velocity at large radii along all the three directions in a galaxy, but their values obtained are smaller by a factor of 2–3 compared to the velocity dispersion values observed already at a galactic radius of a few kpc in Arp 224 and Arp 214.

We suggest that future N-body work should explore the new parameter range covering mergers of a massive satellite with the parent galaxy with values of mass-ratios not covered so far, namely between 1:10–1:4. The simulations of mergers with this mass range are currently lacking. This range can result in a higher increase in velocity dispersion than in the satellite accretion work studied so far, yet avoid the full-scale violent relaxation seen in mergers of comparable-mass galaxies so that the exponential distribution is unaffected. Physically, the above idea has the potential of explaining the unusual, mixed set of properties shown by Arp 224 and Arp 214. An inclusion of gas with the associated dissipation may also be important, but it should have a strong enough effect to affect the distribution of the main mass component namely the old stars that we have studied via the near-infrared.

4. Summary and discussion

High random velocities in mergers are expected theoretically (e.g., Walker et al. 1996), however, it is the combination of exponential profiles and the dominance of velocity dispersion over rotation that we have found here that is unexpected and hard to explain. Thus, the photometric near-IR properties for a new type of sample chosen mainly from its morphologically disturbed appearance (Chitre & Jog 2002), combined with the kinematic data studied in this paper, have together led to a complete and more intriguing picture of these mergers than either data alone would have. The origin and evolution of this new class of observed merger remnants is an open question, and needs further observational and dynamical studies.

The new mass range of 1:10–1:4 proposed here is likely to be common in mergers at high redshift, as shown in the hierarchical merging models (Steinmetz & Navarro 2002) for galaxy formation. Observationally, it is well-known that galaxy morphology evolves with redshift (Abraham & van den Bergh 2001). The two merger remnants studied here appear to be the present-day analogs of the high percentage of peculiar galaxies without well-developed spiral structure observed to be common at high redshift. Thus, the present study may be relevant for the early evolution of galaxies.

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