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Advanced mergers of galaxies: luminosity profiles and dynamics

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Abstract. We have analyzed the near-IR K_s-band data from the 2MASS archival database for a large sample of twenty-seven galaxies that show signs of interaction but have a single nucleus. Surprisingly, half of these advanced mergers of galaxies show luminosity profiles which have an outer exponential fall-off with radius, as in a spiral galaxy (Chitre and Jog 2002). The kinematical data for two of these, Arp 224 and Arp 214, available from the HYPERCAT database were used and these show kinematics similar to elliptical galaxies with the random motion dominating the rotation (Jog and Chitre 2002). The origin of the mixed properties shown by these mergers is a puzzle. To understand these systems, we have recently studied the dynamics of mergers via N-body simulations for unequal-mass mergers covering a new range of galaxy mass ratios 4:1-10:1 (Bournaud, Combes, and Jog 2004). We show that such mergers naturally result in remnants that have the mixed properties as we have observed from the 2MASS data analysis. The transition between elliptical and disk-like remnants is found to occur over a narrow range of galaxy mass ratios 3:1-4.5:1 (Bournaud, Jog and Combes 2005).

Keywords : Galaxies: kinematics and dynamics - Galaxies : interactions - Galaxies: evolution - Galaxies: photometry - Galaxies: structure

1. Introduction

Galaxy interactions and mergers are now known to be common, but their dynamics and evolution are not fully understood. This is an extremely active area in astronomy today. It was proposed theoretically a long time ago that a merger of a pair of equal-mass spiral galaxies results in an elliptical remnant (Toomre 1977). This idea was confirmed for NGC

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7252 observationally in a pioneering work by Schweizer (1982) where it was shown that over a range of $\sim$ 1-40 kpc, the remnant seen in R-band shows an $R^{1/4}$ profile as in an elliptical galaxy. This was shown for a few more mergers in other studies (Wright et al., 1990, Stanford and Bushouse 1991).

In the 1980's - post-IRAS, the above idea became an accepted paradigm as it was realized that galaxy interactions and mergers are very common. Substantial progress was also made in the theoretical N-body simulations of mergers. However, these mostly dealt with equal-mass mergers (Barnes and Hernquist 1991) which also reproduce an $r^{1/4}$ profile. This theoretical work was largely motivated by observations of infrared-bright mergers or ultraluminous galaxies which may not be representative of all mergers. Thus it is not clear if an $r^{1/4}$ profile over the entire galaxy is the only outcome of a galaxy merger.

This was the motivation for our study. We have analyzed the near-IR K_s-band images from the 2MASS archival database for a large, unbiased sample of advanced mergers of galaxies. The idea was to see what a real sample of mergers tells us about the range of possible outcomes. See Chitre and Jog (2002), and Jog and Chitre (2002) for the details of this work. The dust extinction is not important in this band, thus the near-IR emission traces the old stars which constitute the main mass component and hence this is important for understanding the dynamics. The striking result is that half the galaxies studied show a spiral-like luminosity profile but have an elliptical-like kinematics.

We have recently studied the dynamics of mergers via N-body simulations, and specifically looked at the new range of galaxy mass ratios 4:1-10:1. The results obtained naturally explain the peculiar, mixed properties we observed from the analysis of the 2MASS data. See Bournaud et al., (2004, 2005) for the details of this work.

Section 2 describes the data analysis and the results obtained. Section 3 briefly mentions the N-body analysis of unequal-mass mergers and shows that these naturally explain the above observational results. Section 4 summarizes our conclusions.

2. Advanced mergers of galaxies: data analysis

2.1 Sample selection

The sample galaxies were chosen based solely on their optical appearance. Galaxies that show an evidence of an advanced merger such as a single, merged nucleus and yet have obvious signs of tidal interaction such as extended tidal tails, loops, and a puffed-up central body were selected. We chose a sample of 27 such disturbed galaxies from the Atlas of Peculiar Galaxies (Arp 1966) and the Arp-Madore (1987) catalogue of Southern Peculiar Galaxies for which data was available in the 2MASS archival database. 2MASS (Two Micron All Sky Survey) database is maintained at irsa.ipac.caltech.edu . Despite the fact that these systems are messy and dusty in the optical, the near-IR (K_s-band) data used here penetrates through the dust to give the underlying stellar mass distribution. The size of our sample, with 27 galaxies, is large compared to previous studies.

The sample selected was unbiased towards any other property such as the infrared luminosity or the galaxy type. This new selection criterion has led us to the important result of a new class of merger remnants with exponential profiles, whereas the previous studies of mergers mostly used IR-bright systems which gave an $r^{1/4}$ profile as in an elliptical galaxy. As we discuss in Section 3, these represent dynamically distinct systems since the $r^{1/4}$ profile results from equal-mass mergers while an exponential profile results from an unequal-mass merger of galaxies.

2.2 Luminosity profiles

The public-domain, archival data from the 2MASS database were searched to find the 3-D FITS image cubes for each galaxy. From this, the K_s-band images were extracted for each sample galaxy. These were analyzed using the task ELLIPSE in STSDAS in IRAF. Elliptical isophotes were fitted to the images to obtain the azimuthally averaged radial profiles of the luminosity or the surface brightness.

The resulting luminosity profiles show a variety of behaviour, and despite their similar optical appearance, the galaxies fall into two distinct dynamical classes. Nine out of these 27 galaxies showed an $r^{1/4}$ de Vaucouleurs profile as in an elliptical galaxy throughout most of the radial range, we call this Class I galaxies. Of these, four: Arp 156, Arp 165, Arp 225, and Arp 231 were new detections of $r^{1/4}$ profiles in a merger which were not looked at by earlier studies. The Class I galaxies can be explained as arising from mergers of equal-mass galaxies (see Section 3).

Surprisingly, 13 galaxies from our sample could not be fit solely by a single $r^{1/4}$ curve. A simultaneous disk plus an $r^{1/4}$ profile for a bulge was tried but it does not give a good fit. A Sersic or a generalized de Vaucouleurs fit with an $r^{1/n}$ profile (e.g. Caon et al., 1993) was attempted but the resulting value of n is extremely sensitive to the radial range chosen. Hence none of the above fits can be used. Instead each of these 13 galaxies can be fit by an outer exponential disk as in an isolated spiral galaxy. We call these Class II galaxies. The exponential fit is robust in the sense that it typically fits over more than two disk scale lengths and the error bars to the fit are small. This is an unexpected result and its origin is a puzzle, which we address in Section 3.

Typical examples of Class I (Arp 165) and Class II (AM 1315-263) galaxies are shown in Figure 1.

The remaining 5 galaxies do not belong to either of the above two category since they show highly disturbed luminosity profiles and sloshing inner regions. We call these Class III galaxies. These probably represent dynamically highly unrelaxed systems.

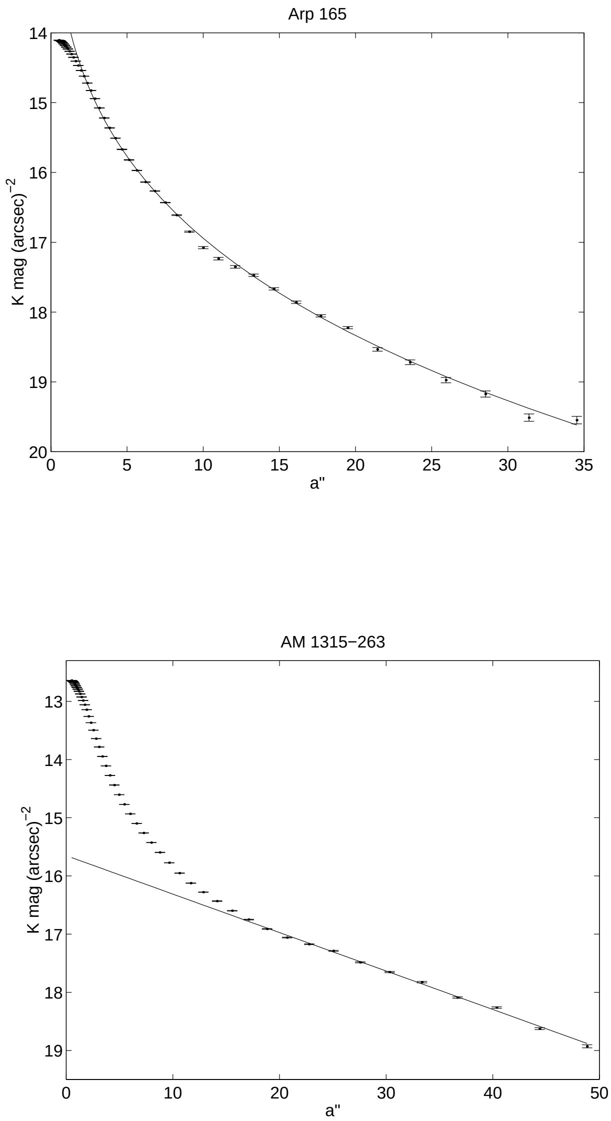

Figure 1. K_s-band surface brightness versus the semi-major axis for Class I (Arp 165) and Class II (AM 1315-263) systems, fit by an $r^{1/4}$ and an outer exponential profile respectively.

2.3 Kinematical properties

To get a better physical picture of the Class II galaxies, we studied the complementary information provided by the kinematics available from the HYPERCAT archives for two of these galaxies, namely Arp 224 (NGC 3921) and Arp 214 (NGC 3718), see Jog and

Chitre (2002) for details. The HYPERCAT archival database is maintained at www-0bs.univ-lyon1.fr/hypercat .

These mergers show a large value of the random velocity dispersion, $\sigma \sim 100$ km s^{-1}, within a few kpc of the galaxy centre. In these systems the velocity dispersion exceeds the rotation velocity, $\sigma/V_c > 1$, similar to that in an elliptical galaxy - see Figure 2 for details. These are somewhat different from typical ellipticals in that here the two values are comparable whereas in an elliptical, one gets $\sigma/V_c >> 1$. In contrast, in a typical spiral galaxy, the rotation dominates the random motion in the disk, $\sigma << V_c$. Thus these galaxies are largely pressure-supported similar to an elliptical system and yet surprisingly show an exponential profile as in an isolated spiral galaxy. Thus galaxy disks are not fragile as has sometimes been suggested but rather these appear to be robust in their radial mass distribution and able to withstand large perturbations. The origin and dynamics of these mergers with such mixed properties is an open question. We proposed an idea based on physical arguments (Jog and Chitre 2002) that unequal-mass mergers with the mass of the satellite galaxy being $> 1/10$ of the larger galaxy could give rise to these, so that the high velocity dispersion could be explained and yet the disturbance would not be strong enough to destroy the exponential mass distribution. This physical conjecture is now confirmed from our N-body simulations- as reported in Section 3.

It would be very useful to have kinematical data on other Class II objects and the Mt. Abu Observatory is ideally suited for this work.

3. N-body simulations of unequal-mass mergers

In order to understand the dynamics of advanced mergers of galaxies, and especially the mixed properties of Class II galaxies (Section 2), we have carried out N-body simulations of mergers of galaxies. The new feature is the study of the new mass ratio of galaxies 4:1-10:1 which has so far not been explored much in the literature. See Bournaud, Combes and Jog (2004) for details. This study has used a powerful FFT N-body code involving a million particles per galaxy and the code also includes the effects of gas and star formation.

The main result is that the above unequal-mass mergers naturally result in remnants that have mixed properties as we have observed for the Class II systems, namely these have mass profiles similar to a spiral galaxy but have kinematics similar to an elliptical galaxy.

Thus our physical conjecture (Jog and Chitre 2002) is now confirmed on a firm quantitative basis. See Figure 3 for results of our simulations for a typical case of a 7:1 merger, seen at 2 Gyrs after the beginning of the simulation (top), which clearly shows the strong tidal interactions and asymmetries similar to those seen in our sample galaxies (Chitre and Jog 2002), while at 4 Gyrs (bottom), the merger is relaxed. This resembles an early-type spiral or an S0 galaxy.

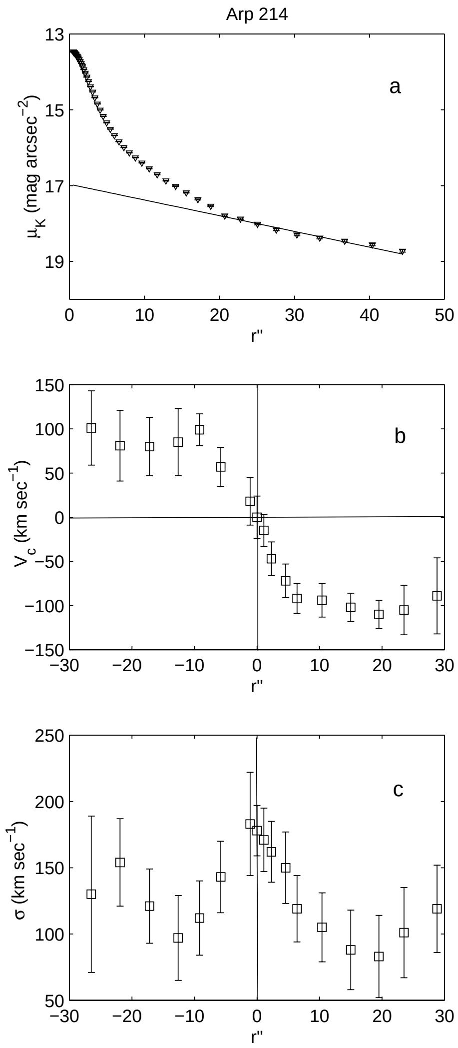

Figure 2. Photometric (a) and kinematic (b,c) properties of a Class II galaxy (Arp 214). The luminosity is fit by an outer exponential (a) as in an isolated spiral galaxy, whereas the kinematics is more like an elliptical galaxy since the rotation velocity (b) is smaller than or comparable to the random motion (c).

Recently, we have carried out an extensive study via N-body simulations of the mergers with a thorough coverage of the galaxy mass ratios (1:1-10:1) and the orbital parameters- for details see Bournaud, Jog, and Combes (2005). One of the important results from this work is that the mergers with the galaxy mass ratios between 1:1 and 3:1 give rise to ellipticals while the range between 4.5:1-10:1 gives rise to remnants with

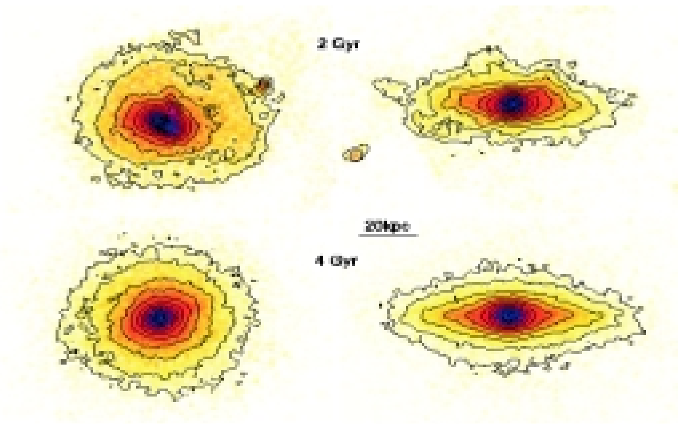

Figure caption: Snapshots of the 7:1 merger simulation (left: face-on – right: edge-on), at different epochs. Top: 2 Gyr after the beginning of the simulation, the system can be regarded as an advanced merger remnant. The nuclei of the two galaxies have merged 400 Myr ago, but strong asymmetries and tidal debris are still visible, as is the case for the systems observed by Chitre & Jog (2002). Bottom: 2 Gyr later, the system is fully relaxed. Its vertical light distribution resembles that of early-type spirals or S0 galaxies.
This is taken from Bournaud, Combes, & Jog 2004, A & A, 418, L27. This work has been supported by the IFCPAR Indo-French grant 2704-1.

Figure 3. N-body simulations of mergers of unequal-mass galaxies

the mixed, hybrid properties of our Class II objects. Thus, interestingly, the transition between elliptical and disk-like remnants occurs over a narrow mass range of 3:1-4.5:1 . This has interesting dynamical implications.

Mergers with unequal-mass ratios as studied here are more likely to occur than the equal-mass mergers which have been studied in the literature so far, since low-mass galaxies are much more numerous than the larger-mass galaxies. Thus our N-body simulations have important implications for the dynamics of mergers and the evolution of galaxies - for details see Bournaud et al., (2005).

4. Conclusions

We have shown that advanced mergers of galaxies with a disturbed morphology can display a variety of profiles including an outer exponential as in a spiral galaxy and not just $R^{1/4}$ as in an elliptical as was long believed. We have found a new class of merger remnants - with an exponential radial mass profile as in a spiral but with elliptical-like kinematics. These properties can be explained by mergers of unequal-mass galaxies (4:1-10:1) as we have shown by N-body simulations. Such unequal-mass mergers are more likely to occur than the equal-mass mergers usually studied in the literature. These have important implications for the evolution of galaxies, especially at a high redshift when the galaxies interactions were more frequent.

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I thank the organizers of this meeting for inviting me for this very useful meeting. Aparna Chitre was was a student at the Physical research Laboratory, Ahmedabad, and did her Ph.D. thesis research using the Mt. Abu telescope, and the observational techniques she learnt then were very useful to us during the analysis of the 2MASS archival data. Thus it is appropriate to report this work at this meeting which is meant to survey the work done in the past decade and make plans for the future work at the Mt. Abu Observatory.

References

Arp, H. C. 1966, *Atlas of Peculiar Galaxies (Pasadena: California Institute of Technology).*

Arp, H.C., and Madore, B. F. 1987, *A Catalog of Southern Peculiar Galaxies and Associations (Cambridge: Cambridge Univ. Press).*

Barnes, J.E., and Hernquist, L.E. 1991, *ApJ*, **370**, L65.

Bournaud, F., Combes, F., and Jog, C.J. 2004, *A&A*,**418**, L27.

Bournaud, F., Jog, C.J., and Combes, F. 2005, *A&A*, In press (also see astro-ph/0503189).

Caon, N., Capaccioli, M., and D'Onofrio, M. 1983, *MNRAS*, **265**, 1013.

Chitre, A., and Jog, C.J. 2002, *A&A*, **388**, 407.

Jog, C.J., and Chitre, A. 2002, *A&A*, **393**, L89.

Schweizer, F. 1982, *ApJ*, **252**, 455.

Stanford, S.A., and Bushouse, H.A. 1991, *ApJ*, **371**, 92.

Toomre, A. 1977, *in The Evolution of Galaxies and Stellar Populations, ed. B.M. Tinsley, and R.B. Larson (New Haven: Yale Univ. Obs.),* **401**.

Wright, G.S., James, P.A., Joseph, R.D., and McLean, I.S. 1990, *Nature*, **344**, 417.