Sloshing and Lopsidedness in Centres of Galaxy Mergers

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Outline of Talk:

- Motivation for studying central luminosity distribution
  - Important for dynamics

- Sample : 12 Advanced Mergers of Galaxies

- Measurement of Central asymmetry :
  * sloshing of centres of isophotes
  * lopsidedness (amplitude of m=1 Fourier component)

- RESULT: High asymmetry, long-lived
  → dynamical implications

Background:

Galaxy interactions and mergers common
→ significant effect on dynamics and evolution

Outer regions of mergers: few kpc – few x 10 kpc well-studied

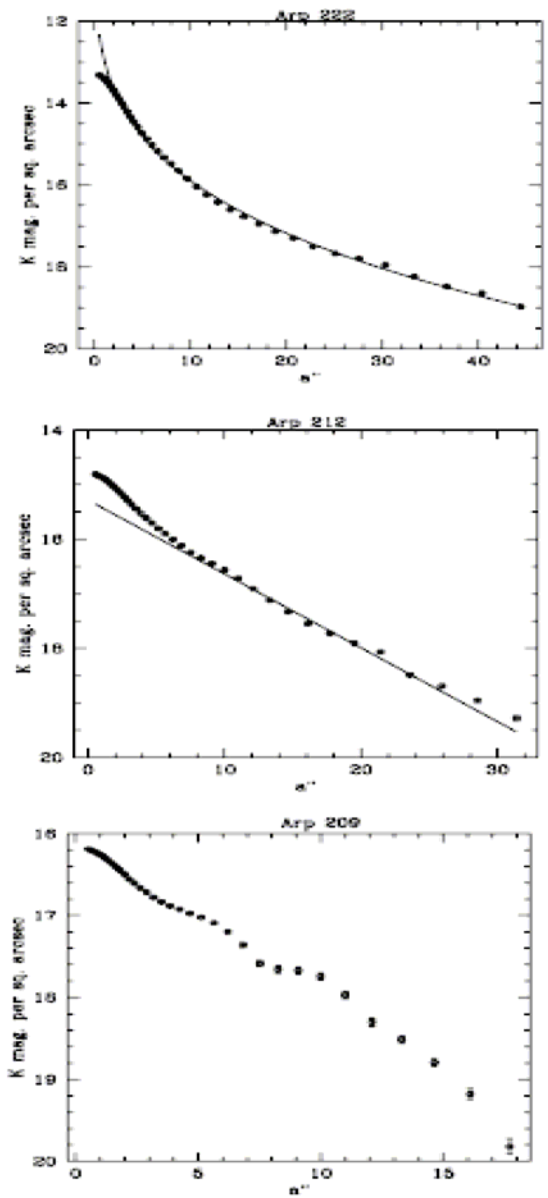
- R^1/4 profile (Schweizer 1982, Stanford & Bushouse 1991)
  -- equal-mass mergers (e.g., Barnes 1992, Naab & Burkert 2003, Bournaud, Jog & Combes 2005)

- Exponential profile shown by half the sample (Chitre & Jog 2002)
  -- unequal-mass mergers (4:1-10:1 mass ratio)
  N-body simulations (Bournaud, Combes & Jog 2004)

  Ages estimated ~ 2 Gyr from simulations

- No-fit in outer parts (Chitre & Jog 2002)
  -- young remnants (< 1 Gyr) – Bournaud et al. 2004

Radial profile of luminosity in mergers:



R^1/4 profile : Class I

Exponential Profile : Class II

No-fit profile : Class III

Chitre & Jog 2002

In Contrast, Luminosity Distribution in Centres of Mergers –
Not studied well so far.

However, important for understanding the central relaxation & dynamics.

Previous work : Isophotal analysis – non-concentric isophotes or wandering centres NGC 3921 (Schweizer 1996), Arp 163 (Chitre & Jog 2002)

We measure non-axisymmetry in centres of 12 Merger Remnants
(Jog & Maybhate 2006, MNRAS, 370, 891)

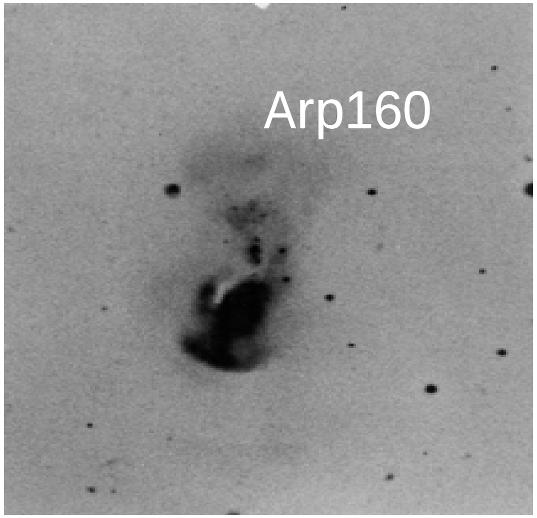
-- based on 2MASS near-IR data
→ traces underlying stellar mass distribution
since dust extinction not important

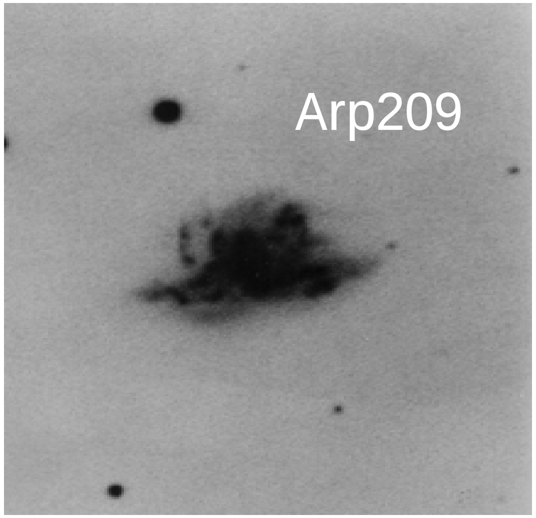
SAMPLE selection: 12 Advanced mergers of galaxies

- showed single nucleus, yet signs of interaction such as
  extended tails, loops, puffed-up central body
- angular size > or ~ 20-24” (~ use 5-6 annular rings
  of 4” width = twice 2MASS resolution)
- cover all classes (r^1/4, exponential, no-fit profile)
  → to study the dependence on mass ratio, age of remnants
  (from Arp and Arp-Madore catalogues)
- SAMPLE: Arp 221, 222, 225, AM 0612-373
  Arp 162, 212, 224
  Arp 160, 163, 209, 254, AM 1025-433

Is it surprising to see central asymmetry in mergers?

On large scales ~ 30-40 kpc, mergers are highly non-axisymmetric





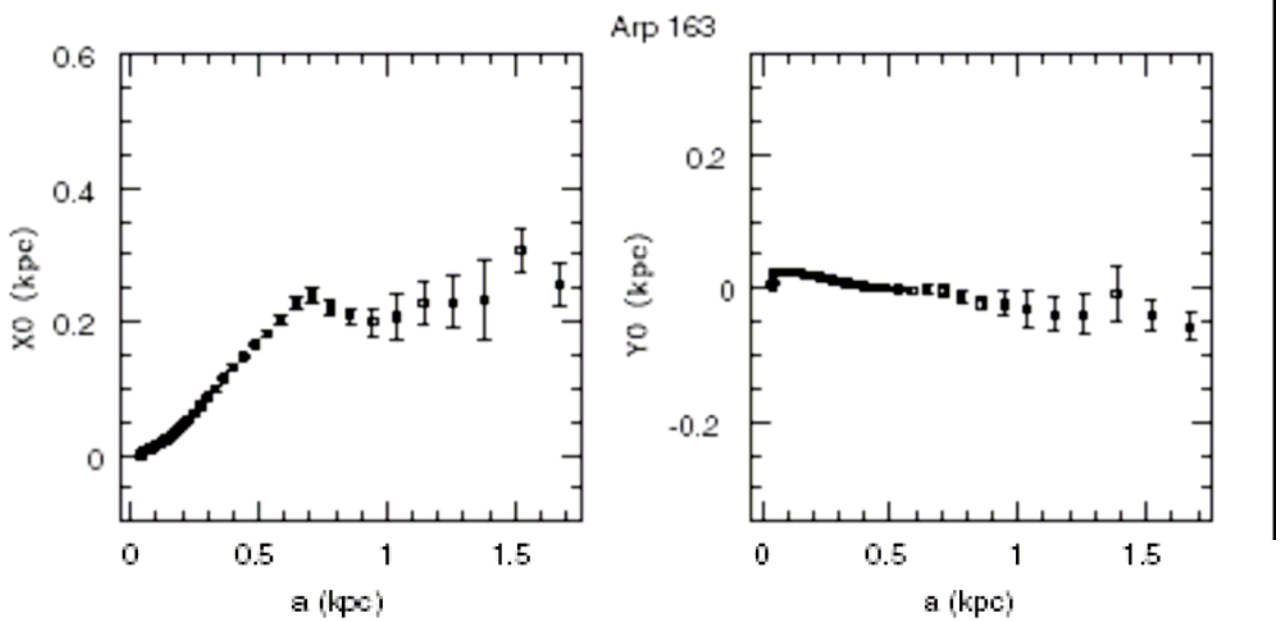
However, inner regions~ 10 kpc show some relaxation → merged centres and a smooth radial profile.

Central regions (< few kpc) ?? t_dynamical smaller hence expect to be more relaxed -- Find opposite is true !

RESULTS: 1. Isophotal Analysis - Sloshing of centres

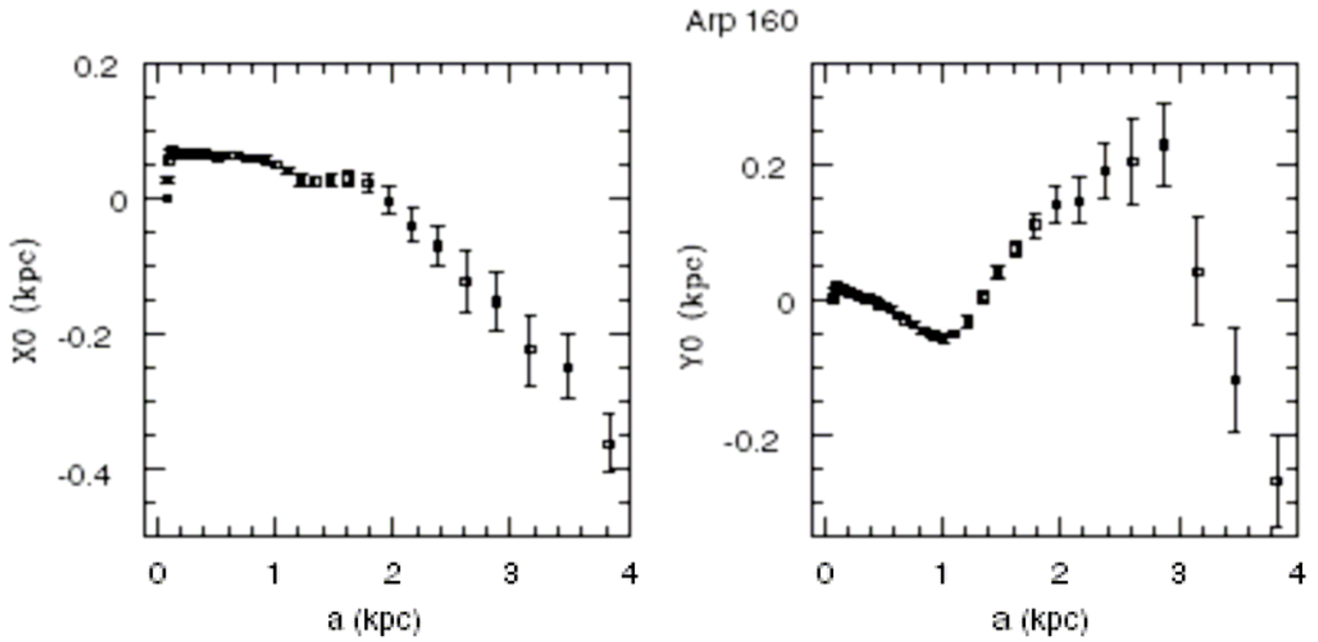
- K_s band images from 2MASS analyzed using ELLIPSE (STSDAS) – Elliptical isophotes were fitted to galaxy images while allowing centre (x_0,y_0) , elllipticity, PA to vary to get the best fit.

- **Centres X_0,Y_0 of subsequent isophotes do not coincide** ---- instead show a striking wandering or sloshing pattern



Plot of Centre X_0,Y_0 vs. a, semi-major axis of isophotes

Sloshing of isophotal centres in another merger: Arp 160



Average values of Sloshing within central 1 kpc

- Define normalized sloshing as $[(X-X_0)^2 + (Y-Y_0)^2]^{1/2} / a$

- Mean value of sloshing in central 1 kpc is high
  ~ 0.1 - 0.2
  This indicates a dynamically unrelaxed region.

- Surprisingly the central regions are not relaxed
  (even 1-2 Gyr after the merger)
  → even when the outer regions have a smooth mass distribution (r^1/4 or exponential)

The origin and dynamics of sloshing are open questions .

2. Non-axisymmetric Amplitudes: Fourier Analysis

Galaxy Images from 2MASS were Fourier-analyzed, to get amplitudes and phases of Fourier components (m)

→ measure the deviation from axisymmetry

Used J-band data as it goes deeper → study upto larger radii

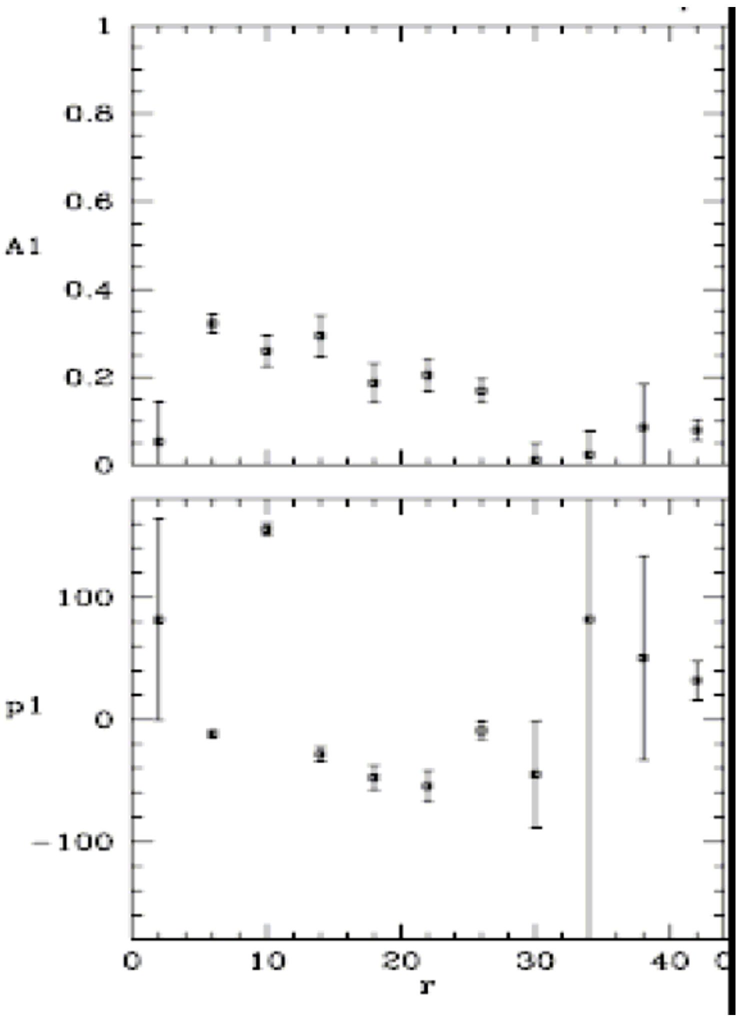
Divide the image into annular bins (of size > 4") w.r.t. a constant centre (stellar max)

Fit the complete 2-D data to obtain the fractional Fourier amplitude A_1 (lopsidedness), phase P_1 , and for higher m.

Result: Mergers show strong lopsidedness

Average $\langle A_1 \rangle$ values within 5 kpc are ~ 0.12-0.16

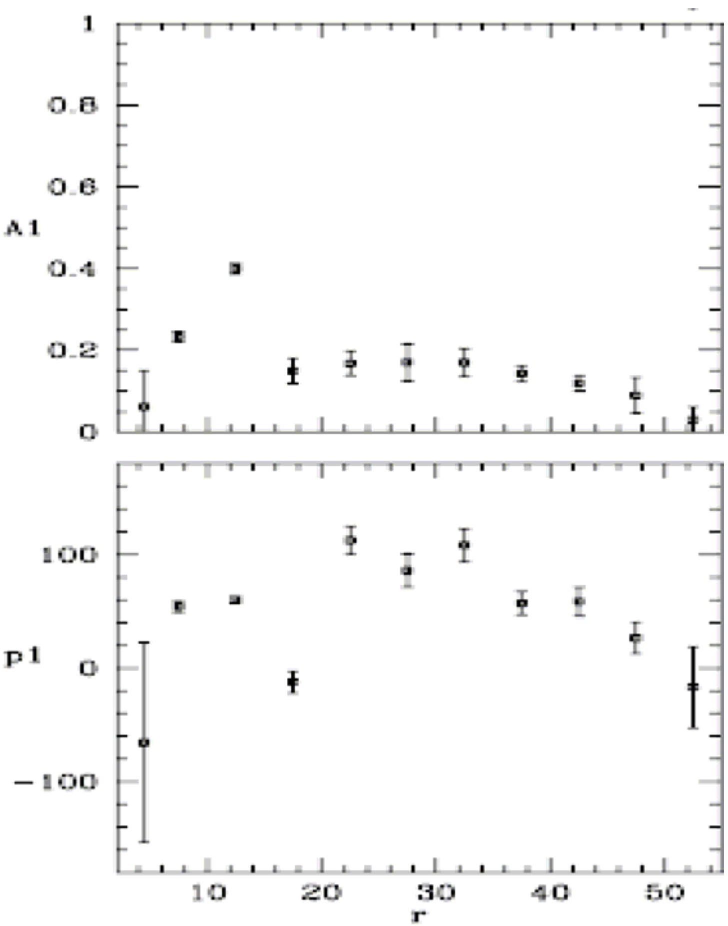
Lopsided amplitude A_1 and phase P_1 vs. R in centre of Arp 163



Strong lopsidedness:
and amplitude A1 peaks at an intermediate radius

Phase P1 shows large fluctuations

Lopsided amplitude A_1 and phase P_1 vs. R in centre of Arp 224



In merger centres, A1 peaks at intermediate radius, and phase fluctuates with radius

In contrast: Normal galaxies, A_1 increases with radius, & phase P_1 ~ constant (global mode) (Rix & Zaritsky 1995, Bournaud et al. 2005)

→ DIFFERENT ORIGIN of Lopsidedness in mergers

Comparison with normal spiral galaxies:

Similar non-axisymmetric analysis for a control sample of 8 galaxies

Selection of “non-merger” galaxies – non-trivial !
avoid early-type galaxies, or with bars, or active
→ To ensure that these have had no interactions in recent past

Choose Large angular size, nearly face-on galaxies
(from Large Galaxy Catalog- Jarrett et al. 2003)

Result: These show much smaller central lopsidedness ~ 0.04
vs. 0.12-0.16 in mergers

& smaller central sloshing values ~ 0.07
vs. 0.1 – 0.2 in mergers

Confirms that origin of high lopsidedness and sloshing seen in mergers can be attributed to the merger history.

Dynamical implications of High Central Asymmetry :

1. Long-lived Central Asymmetry:

- Ages of merger remnants deduced as ~1-2 Gyr
  (from N-body simulations Bournaud, Jog & Combes 2004)
  -- see next slide

- Central T_dynamical ~ few kpc/ few 100 km/s
  ~ 10^7 yr

Thus, central asymmetry is long-lived ~ 100 local dynamical timescales

- Hence, Important for fuelling of central AGN
- Also, for secular bulge-building (~ to bar-driven bulge growth)

Need future theoretical study.

Merger remnants for 7:1 mass ratio

(Bournaud, Combes & Jog 2004)

L28 F. Bournaud et al.: Unequal-mass galaxy merger remnants: Spiral-like morphology but elliptical-like kinematics

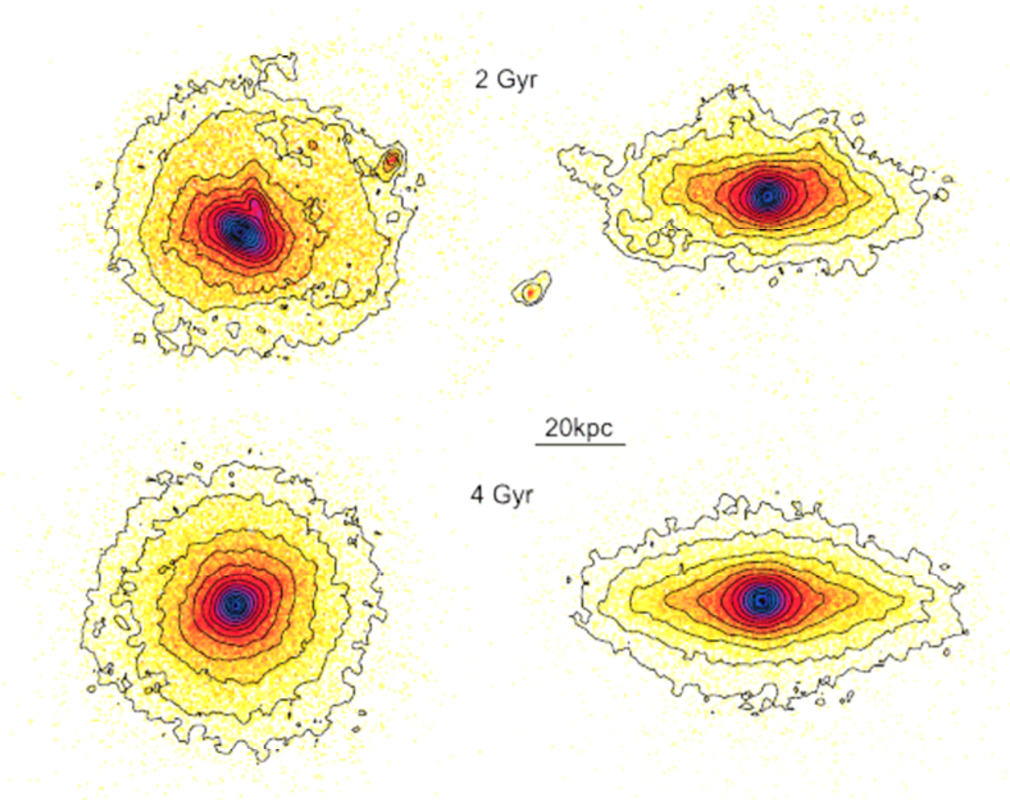


Fig. 1. Snapshots of the 7:1 merger simulation (*left*: face-on – *right*: edge-on), at different epochs. *Top*: 2 Gyr after the beginning of the simulation, the system can be regarded as an advanced merger remnant. The nuclei of the two galaxies have merged 400 Myr ago, but strong asymmetries and tidal debris are still visible, as is the case for the systems observed by Chitre & Jog (2002). The morphological and kinematical analysis (Figs. 2 and 3) has been done at this epoch, to reproduce the observations of 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.

Upto ~ 1.5 Gyr the remnant appears disturbed (top panel), after another 2yrs it shows no traces of interaction (lower panel) hence would not get selected in the Arp Catalog or our sample.

Dynamical implications of High Central Asymmetry :

2. Dependence on age, mass ratio

The asymmetry (lopsidedness and sloshing) stronger for younger remnants (< 1 Gyr)

But no clear dependence on mass ratio M_1/M_2 of galaxies

3. Origin and Evolution of Central Asymmetry ??
Relation of lopsidedness to sloshing?

LOTS OF OPEN QUESTIONS !!