THE DYNAMICAL PROPERTIES OF MERGERS

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How do we go from:

To:
And what is the end-product?
OUTLINE

1. Stars, Dissipation, Central Densities
2. “Fundamental” Correlations
3. Rotation or Anisotropy?
4. Final Thoughts
**Toomre Hypothesis** (TT’72, T’77):

- Mergers between two spiral galaxies produces an elliptical galaxy
- The Merger occurs quickly
- Interaction “stokes the furnace,” dredging “fuel” and triggering intense star-formation

**Important Physics:**

- **Tidal Friction:** energy transferred from the orbits produces tidal features.
- **Orbital Decay:** transfer of energy leads to breaking and orbital decay, eventually forcing the objects to merge.
- **Violent Relaxation:** Potential of the system changes due to encounter. Stars are scattered, some gain energy, some lose. End result is *approximately* an $r^{1/4}$ stellar distribution.
- **Dissipation:** Gas is funneled to the barycenter of the merger. Gas can trigger star-formation. Gaseous inflow can also form a new central gaseous disk.
- **Phase Mixing:** Once correlated orbits are altered. Over time, stars with different periods “smooth” out structure. Timescale ~ 1+ Gyr after the merger.
Properties of Early-Type Galaxies

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Absolute Magnitudes of E and S0 Galaxies in the Virgo and Coma Clusters as a Function of U - B Color

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Rotation (?) in 13 Elliptical Galaxies
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Received 1977 August 12; accepted 1977 September 13

The Kinematic Properties of Faint Elliptical Galaxies
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Paul L. Schechter3
Received 1982 March 23; accepted 1982 August 20

Fundamental Properties of Elliptical Galaxies
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The Stellar Distribution

- Violent Relaxation should produce an $r^{1/4}$ distribution for cold and irregular initial conditions; Barnes (1996) pointed out disk-disk mergers shouldn’t automatically produce $r^{1/4}$ profiles.

- Violent relaxation smoothes the transition between the progenitor profiles (bulge+disk) and the outer exponential disk *(what about Sc-Sc mergers?)*

- Dynamics Range is critical: important whether the outer part of SB $\approx r^{1/4}$; Need: 1) Deep observations to sample faint light, 2) wide FOV

- Want to measure the “right” stars in mergers
  - Optical light contaminated by young, hot stars
  - IR - old, late-type stars dominate light - stars which make up majority of mass
51 Advanced Merger Remnants

- $\mu_k \sim 21$ mag/arcsec$^2$ (R>10kpc)
- 0.8" median seeing ~ (100-500pc)
Central Densities

- Original objection, summarized by Gunn (1987): “I do not think you can make rocks by merging clouds.”

- $f \propto L^{-2.35}$ (Carlberg 1986)

- Disk-Disk dissipationless mergers can’t make intermediate mass ($\approx \text{sub } L^* - 1L^*$) ellipticals (Kormendy 1989)

- Very luminous disk-disk mergers could form massive ellipticals – but there is $\sim 10-20\%$ deficit of high phase-space density material in the central regions (Hernquist et al. 1993)
How Do We Justify Invoking Dissipation?

Larson & Tinsley 1978

Wang et al. 1992

Hibbard et al. 1994

Schweizer 1982

Sanders 1988

Goldader et al. 1997

Wang et al. 1992

Hibbard et al. 1994

Whitmore et al. 1999
**Dissipation Predictions**

- Prediction (MH94,S00) - should observe an upturn in stellar luminosity profile *(had yet to be observed)*

- Dissipation produces a strong starburst which creates a dense stellar core

- Hibbard & Yun (1999) modeled the predicted luminosity profile based on $B$-band data + observed gas
  - 2/3 mergers will eventually form seamless profile between new+old stars,
  - Arp 220 (ULIRG) might retain an anomalous profile

Inhibitor

Mihos & Hernquist 1994

Springel 2000

Hibbard & Yun 1999
How Does Dissipation Affect the Observables?

- Rothberg & Joseph (2004) found evidence of “excess light” in 1/3 of the 51 K-band light profiles of advanced merger remnants
- HY99 and RJ04 found amount of excess light smaller than predicted
- Luminosity density of mergers higher than typical E/S0s; should fade over time (Rossa et al. 2006)
  - (see poster #26 - Joern Rossa)
- Question remains: Once tidal tails fade and most structure is smoothed away, will Es retain the anomalous stellar profile?
  - (see poster by #18 - Jodie Martin)
Phase-Space

- Hernquist (1993) defined a measure of coarse-grained phase-space density based on observables:
  \[ f_{\text{eff}} \equiv \frac{1}{\sigma_0 R_{\text{eff}}^2} \]

- Strong overlap with ellipticals from Pahre (1999). ULIRG/LIRG show statistically notable higher \( f_{\text{eff}} \) than the ellipticals

- Suggests mergers have undergone dissipation

Rothberg & Joseph 2006a
Fundamental Correlations

- Internal motions correlate with luminosity
  - Faber-Jackson (1976) two-parameter: $\sigma \propto L$
  - Djorgovski & Davis (1987) three-parameter: $\sigma$, $\langle \mu \rangle$, $r_{\text{eff}}$

- Can use Virial Theorem to derive similar relationship, assuming:
  1) homologous structural parameters
  2) $M/L \propto L$ constant

- Lake & Dressler (1986) used $B$-band w/MgIb & Ca triplet absorption lines
  - Concluded IR light + “IR” stellar lines (Ca triplet) best combination

- Subsequent studies (Doyon et al. 94; Shier et al. 94, 96; Shier & Fischer 98; James et al. 99; Genzel et al. 01; Tacconi et al. 02; Dasyra et al. 06) have used CO (2.3 $\mu$m) & primarily focused on LIRGs/ULIRGs
**K-band Fundamental Plane**

- **κ-space projection** (Bender et al. 1992)
  - Mass is consistent with $E_s$ over entire mass range
  - $M/L$ drop off

**K-band Fundamental Plane for 38 advanced (single-nuclei) merger remnants**

- $\sigma$ measured with Ca triplet

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Rothberg & Joseph 2006a
Comparison of Kinematics

- Comparison of $\sigma$ among various types of galaxies

- In terms of $m^*$:
  - Rothberg & Joseph 2006a:
    - Total Sample Mean: 1, Median 1.4
    - LIRG/ULIRGs: 0.88
  - Dasyra et al. 2006 LIRGs
    (single nucleus/nuclei < 1kpc separation)
    - Mean 0.63

Rothberg & Joseph 2006a Kinematics from optical spectra, except “Previous LIRG/ULIRG” Studies (CO 2.29µm)
Do we always get the same answer?

- Discrepancy between optical & infrared stellar lines
- Early-type galaxies show $\sigma_{\text{IR}} < \sigma_{\text{optical}}$ (Silge & Gebhardt 2003)
- LIRG/ULIRG merger studies: $m < m^*$
- Lake & Dressler (1986), Rothberg & Joseph (2006a) show mergers (including LIRG/ULIRG) with larger $\sigma$
- Silge & Gebhardt compared dust, EWs and structure: disky early-types show largest discrepancy
- CO absorption line is degenerate diagnostic - sensitive to both metal-rich giants and metal-poor red supergiants
- If starburst forms younger stellar population in situ, CO may be detecting a central stellar disk
Mass-Metallicity Relation

- Ellipticals show a strong correlation between mass and metallicity (Tonry & Davis 1981; Terlevich et al. 1981; BBF93)

- Semi-analytical $\lambda$-CDM models predict a tight Mg-$\sigma$ relation (e.g. Kauffman & Charlot 1998)

- Some mergers follow the same trend (Rothberg & Joseph 2006a)

- Offset from FP anti-correlated with line strength; similar results seen by Forbes et al. (1998) & Michard & Prugniel (2004) for peculiar ellipticals

![Graphs showing correlation between mass and metallicity](Rothberg & Joseph 2006a)
Mass-Metallicity Relation: Will the mergers match Es? (and if so, what kind and how can we tell)

- Evolution from starburst --> K+A --> ?
  (see Poster #24 - Thomas Puzia)
- Observed [Mg/Fe] overabundance ([α/Fe] enhancement) in luminous Es
  - 1) merging must occur early in chemical enrichment of parent spirals;
  - 2) $\tau_{\text{burst}} \sim 10^7$ yr
- Howell (2006) - “King Gap” Ellipticals
  - 6 Es selected based on tidal HI debris
  - 2/6 consistent with predictions for a merger origin
How are shape and dynamical support linked with formation?

- Amount of rotation or anisotropy coupled with isophotal shapes (boxy/disky) may provide clues to how elliptical galaxies formed.

- Kormendy & Bender (1996) suggested that isophotal shapes are directly correlated with the presence or absence of dissipation during formation.
What do mergers give us?

- First simulations (e.g. White 1979) predicted $V/\sigma = 0.65$, at that time larger than any observed values in ellipticals

- Boxy ellipticals have been linked with mergers
  (e.g. Binney & Petrou 1985; Governato et al. 1993; Schweizer et al. 1990; Heyl et al. 1994)

- Inclination effects may make it difficult to disentangle boxy & disky
  (e.g. Hernquist 1993; Naab et al. 1999; Naab & Burkert 2003; Gonzalez-Garcia & Balcells 2005)

- How does dissipation affect the orbits?
  - If gas accumulates in the central region, potential well deepens, prolongs violent relaxation phase
  - Deep potential wells restrict range of potential orbital shapes
    (see Barnes 1996)
  - Dissipation of gas (not including star-formation) produces a central gaseous disk – affects isophotes
    (Naab et al. 2006)
    (e.g. Barnes & Hernquist 1996; Barnes 2002)
  - Non-axisymmetry in centers (Jog & Maybhate 2006)

- Rotation Curves: De-coupled cores could be a merger signature
  (e.g. Hernquist & Barnes 1991, Bender & Surma 1992; Koprolyn & Zeilinger 2000)
V/σ Plane

- NGC 1316 $V/σ = 0.64$ (Bosma et al. 1985), places it just above oblate rotator ($ε = 0.2-0.2$)

- Lake & Dressler measured $V/σ$ for three mergers, 0.43, 0.23, 0.58 (NGC 2418, NGC 2919, NGC 2914) –just below or on oblate rotator

- NGC 3640, boxy, bright, fast rotator, possibly triaxial (Prugniel et al. 1988)

- 37 merger remnants show clustering near oblate line, but some have small $V/σ$

- No $V/σ < 0.10$, or $V/σ^* < 0.21$ –Rothberg & Joseph 2006b
  - Dasyra et al. (2006) measured $V/σ$ for a sample of ULIRGs only, similar findings
• **Comparison w/Naab et al (2006) models:**
  - Mergers overlap w/3:1 mass ratio – no gas
  - Models with gas component, but no star-formation consistent with wider range of mergers

• **Observed mergers show properties similar to “forbidden” properties in simulations**
  - bright, slow rotating with disky isophotes
  - this has not been seen (yet?) in ellipticals – projection? Triaxiality?

• **Mergers consistent with both bright E’s & intermediate E’s**

• **REMINDE:** NGC 1316 – boxy isophotes, rotates (Schweizer 1980; Bosma et al. 1985)
Stellar Rotation Curves

- Several observations of Kinematically de-coupled cores (KDC) in Mergers - NGC 3656, NGC 1700 -post merger E (Statler et al. 1995)
- Prolate or triaxial - NGC 3923, shell E (Carter et al. 1998) -possible KDC
- Genzel et al. (2001) show decoupling between stellar & gaseous rotation in Arp 220
Phase Mixing

• How well mixed are mergers?

• Two methods:
  • 1) Unsharp mask – Divide by 3-pixel median mask – Removes small scale fluctuations (left)
  • 2) Residual Image – Subtract best-fit model – good for looking at large scale structure (i.e. tidal tails) – (right)

• Three examples:
  • NGC 455
    • rectangular core (boxy isopotes)
    • residual nearly featureless
  • NGC 3921
    • oval core
    • tidal tails
  • AM 0612-373 –
    • diffuse core
    • “pinwheel” residual known to be feature of disk objects
    • Disky isophotes
    • $\sigma = 303$ km s$^{-1}$
    • $M_K = -25.6$

Rothberg & Joseph 2004
Local Mergers on the Move...

- Quick look at where local mergers lie on Red Sequence/Blue Cloud
  - 16 mergers from Rothberg & Joseph sample
  - 5 LIRGs/ULIRGs
  - $80 \text{ km s}^{-1} < \sigma < 288 \text{ km s}^{-1}$
  - Full range of Sersic values ($1 < n < 10$)

- What would mergers look like at high-$z$?
- Tidal features remain out to $z \sim 1$ (assuming HDF exposure times)
- At $z > 1.5$ morphologies reflect most active regions (UV knots)
- Photometry fails to recover true global properties, including missing older, evolved (red) stellar population, where most of the mass lies

Hibbard & Vacca 1997

Blanton et al. 2003

Re-plot of Bell et al. 2004 (courtesy of Rachel Somerville)
Final Thoughts: Where does this leave us?

Dissipation is important & necessary for mergers in the local universe

1. The old stellar populations in mergers show nearly the same stellar distribution as elliptical galaxies

2. Signatures of dissipation/starburst found in surface brightness profiles of both mergers and ellipticals

3. Evolution of mass-metallicity relation (mergers --> Es)

4. Spiral-spiral mergers can form both intermediate-mass and some giant ellipticals
   A. Which absorption line do you trust?
   B. *Is V/σ or V/σ* a way to sort origin of brightest Es?*
   C. Isophotal Shapes don’t always match strict boxy-bright-anisotropy or disky-faint-rotation paradigm