Evolution of Star Clusters on Eccentric Orbits

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Cai et al. (2016), MNRAS, 455, 596

7th KCK meeting, NAOC, Dec 15, 2015
Dissolution of Star Clusters

• Stars are formed in clusters (Lada & Lada 2003)

• Star clusters gradually dissolve due to internal and external mechanisms

• How does the parent galaxy play the role of the dissolution of its star clusters?
Dissolution of Star Clusters

Internal Effects

• **Primordial gas loss** (e.g. Goodwin 1997; Kroupa et al. 2001; Boily & Kroupa 2003; Lada & Lada 2003)

• **Stellar evolution** → mass loss → weakens the binding of the cluster (e.g. Applegate 1986; Fukushige & Heggie 1995; Giersz 2001; Baumgardt & Makino 2003)

• **Two-body relaxation** → expansion and evaporation (e.g. Spitzer & Chevalier 1973, Antonov 1962, Lynden-Bell & Wood 1968)

External Effects

• **External tidal fields** → lowers the limiting energy for bound stars (e.g. Spitzer 1987)

• **Dynamical friction** → Orbit decay (e.g. Chandrasekhar 1942)
Equipotentials in the Cluster Frame

Credit: D. C. Heggie
Modeling External Tidal Fields

Constant tidal fields on circular orbits

• Analytical: e.g. Héron 1961; King 1966; Gieles, Heggie & Zhao 2011

• Numerical: e.g. Chernoff & Weinberg 1990, Oh & Lin 1992

Varying tidal fields on eccentric orbits

• Numerical: Baumgardt & Makino 2003; Webb et al. 2014
Circular verses Eccentric Orbits

• How does the evolution of cluster on eccentric orbits compare with that on circular orbits, **if they have the same dissolution time**?

• Is it possible to approximate the evolution of clusters on an eccentric orbit, but that of a star cluster on circular orbit?

• If so, it would greatly simplify the treatments of fast semi-analytical model for eccentric orbits, which are currently limited to circular orbits.

• What is the dominant mechanism of the dissolution of star clusters on eccentric orbits?

• **Baumgardt & Makino (2003):** dependency of lifetime on eccentricity, half-mass relaxation time, mass of the individual star.
Initial Conditions

- \( N = 8000, 16000 \) equal-mass systems
- No stellar evolution
- \( G = M = -4E = 1 \)
- Plummer model, virial radius: \( r_v = 1\text{pc} \)
- \( e = 0.0, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8 \)
- Keplerian potential, galaxy mass = \( 10^{10} M_\odot \)
- Initial filling factor: \( r_h/r_t = 0.1 \)
- Direct \( N \)-body simulations

Integrator: NBODY6tt (Renaud et al. 2011)
Apogalactic Radii with the same dissolution time

<table>
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<th>N</th>
<th>T_{diss}</th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
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</table>

- Initial guess (BM03): \( R_a = R_G / (1 - \epsilon)^{(2/3)} \)
- Find the \( R_a \) iteratively by linear interpolation of \( (0.8R_a, 1.0R_a, 1.2R_a \) and \( 1.4R_a) \)
• Initial filling factor: $r_h / r_j$

• For a discussion of the sensitivity of the Roche-filling models of BM03 to stellar mass-loss, see Contenta, Varri & Heggie (2015).

$$r^3_j = \frac{GM}{\omega^2 - \frac{d^2 V}{dR^2}}$$  \hspace{1cm} r_h \approx 0.78 r_v$$
Normalized to the Circular Orbits

- To first order, dissolution time is independent of the eccentricity and $N$ for orbits with the same semi-major axis (Bar-Or et al., in prep.)

- Higher order terms to be derived later by scaling all models to the same semi-major axis
Result I: Bound Mass

Bound mass evolution profiles resemble each other regardless of eccentricities.
Result II: Half-mass Radii

Half-mass radius evolution profiles resemble each other regardless of eccentricities.

$T_{CC} \sim 0.3 \tau_{diss}$
Escaping rate doubles after core collapse (Lamers, Baungardt & Gieles 2010)
Result III: Dissolution Time as a function of Eccentricity with the Same $R_a$

- Equal-mass, no stellar evolution → It is possible to scale the existing results without running extra simulations
- Scaling all models to the same apogalactic radius
- Direct comparison with BM03
- Stronger dependency of eccentricity in point-mass galactic potential than isothermal potential (BM03)

$$R_* = \frac{R_a(0)}{R_a(\epsilon)}$$

Point mass $r_* = R_*$ $t_* = R_*^{3/2}$

Isothermal $r_* = R_*$ $t_* = R_*$
Result IV: Dissolution Time as a function of Eccentricity with the Same Semi-major Axis

- Equal-mass, no stellar evolution $\rightarrow$ It is possible to scale the existing results without running extra simulations
- Scaling all models to the same apogalactic radius
- Galaxy profiles, initial filling factors, stellar evolutions, $N$ could all play their roles
- Even functional form for fitting

$$R_* = (1 + \epsilon)R_a(0)/R_a(\epsilon)$$

Point mass: $r_* = R_* \quad t_* = R_*^{3/2}$
Isothermal: $r_* = R_*^{3/2} \quad t_* = R_*$
Conclusions

• Modeled with direct N-body simulations.

• **YES!** Eccentric orbits $\leftrightarrow$ circular orbits

• Dissolution time independent of eccentricity and galactic mass profile to the first order for orbits with the same semi-major axis; higher order terms are empirically derived.

• Higher order dependency of eccentricity caused by galactic mass profile, IMF, stellar evolution, cluster mass, etc.
Applications

• Useful for modeling techniques that are not able to include orbital eccentricity, such as Monte-Carlo method and/or time-dependent galactic tides. (e.g. Heggie & Giersz 2008).

• Semi-analytical models of cluster evolution (e.g. Gnedin, Ostriker & Tremaine et al. 2014).

• Benchmark for theoretical studies of the escape rate from clusters on eccentric orbits.
Movie!
Thank you!

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