Introduction to the dynamics of collisional stellar systems: the early life of star clusters

Partit

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Outline-Lec2

- -The effect of Primordial mass segregation and early gas expulsion on the Survival and Dissolution of Star Clusters
- -Direct Nbody modeling of realistic MW
- Application to the Globular Clusters system in M31
- -The effect of Metallicity- and Density-Dependent IMF

Mass Loss From Star Clusters Stellar & Dynamical Evolution

Characteristic parameters of star clusters change with time at early stages and also during the cluster long-term evolution

Vesperini & Heggie 1997; Giersz & Heggie 1996, **Baumgardt & Makino 2003**, Zonoozi et al. 2011, 2014, 2017, Haghi et al. 2015, Bianchini et al. 2017, webb et al 2017, MC method : Giersz et al. , Rasio et al.,

Internal and External Mechanisms:

- Stellar evolution and gas expulsion

- Two body (collisional) relaxation: energy equipartition and mass segregation, binary heating, 3 and 4-body encounters, core evolution

- Violent relaxation: Tidal interactions, dynamical friction, bulge/disk shocking, tidal stripping

The effect of Primordial mass segregation on the evolution of star clusters

Consequences of 2-body relaxation: Dynamical Mass segregation



As a result of energy equipartition, the heavier stars tend to move toward the cluster centre while lighter stars tend to move further away from the cluster centre.

Primordial Mass Segregation (PMS)



Primordially segregated clusters, leads to a stronger expansion than for initially non-segregated clusters.

The effect of early gas expulsion on the evolution of star clusters



Evolution of the parameters of star clusters:

Stellar Mass Function, Radius, mass-to-light ratois,

Direct N-body simulation of GCs

I. Modeling of Palomar 14 Zonoozi et al 2011, MNRAS

II. Modeling of Palomar 4 Zonoozi et al 2014, MNRAS

Highly flattened Mass Function



Flatter than Canonical Kroupa IMF

$$\alpha = 2.35$$

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Highly mass segregated



Flattening of the stellar mass function (MF) of GCs

- Star clusters evolve at early stages and also during the cluster evolution as the stars are removed from the system through **stellar** and **dynamical** evolution.
- Vesperini & Heggie (1997); Baumgardt & Makino (2003).

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Direct N-body simulation of the MW GCs

Modeling of Palomar 14 Zonoozi et al 2011, MNRAS

- Distance: 71± 1.3 kpc
- Half-light radius = 26 pc

Extremely extended clusters

Modeling of Palomar 4

Zonoozi et al 2014, 2017 MNRAS

- Distance: 102 ± 2kpc
- Half-light radius = 18.5 pc

Trlx > TH

Initial conditions of Pal 14 & Pal 4

- Only models with both a **flattened IMF** and a very high degree of **primordial mass segregation** would be necessary to explain the MF flattening. (Zonoozi et al 2011, 2014)
- They might be born mass segregated and then went through a violent gas-expulsion epoch after being born which inflated the cluster and depleted its low-mass stellar content.

Birth Conditions before gas expulsion?

Combined Effect of Gas Expulsion and Primordial Mass Segregation

Flattening of the stellar mass function (MF) of outer halo GCs: Pal 4 and Pal 14 (Zonoozi et al 2011, 2014, 2017)



The flattening of the MF-slope driven by a violent early phase of gas-expulsion (GE) of an embedded cluster with primordial mass segregation (Haghi et al. 2015)

The influence of gas expulsion on the MF of primordially mass-segregated model



Pal 4 on eccentric orbit !

Pal 4 at R_G=100 kpc is tidally-underfilling, and shows no flattening if we assume it on circular orbit.

The cluster formed in a stronger tidal field rather than in isolation

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But most globular clusters move on eccentric orbits



Possible solution for the flattened MF of Pal 4/14 Zonoozi et al. 2017.

Eccentric Orbit+ Primordial mass segregation+ canonical IMF

The best-fitting model:

Mi=100,000 R_h=3 - 4 pc

Eccentric orbit with e ~ 0.9 Rp ~ 5 , Ra=110 kpc

Highly mass segregated Kroupa IMF

Model	$\begin{array}{c} r_{hl}(pc) \\ (\pm 2.1) \end{array}$	$\begin{array}{c} R_h(pc) \\ (\pm 2.8) \end{array}$	$M_{obs}({ m M}_{\odot})\ (\pm 215)$	$M_{tot}(M_{\odot}) \ (\pm 2500)$	$_{(\pm 0.13)}^{\alpha}$	$\begin{array}{c} \sigma_{los}(km/s) \\ (\pm 0.07) \end{array}$
Observations ($\alpha_{low} = 1.3$) Observations ($\alpha_{low} = -1.0$)	18.4±1.1		5960 ± 110	29800 ± 800 20100 ± 600	1.4 ± 0.25	0.87±0.18









Prediction of Proper Motion of Pal 4

Zonoozi et al. 2017.



New measurements confirms our prediction for proper motions:

Pal 4 most likely orbiting on a highly eccentric orbit with e ~ 0.9, Rp ~ 5 kpc, Ra=110 kpc

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New measurements confirms our prediction for proper motions:

E. Vasiliev (arxiv. 2018): GAIA-DR2 \mu_alpah= -0.145 pm 0.085 \mu_delta= -0.516 pm 0.168

The uncertainties are too large

Pal 4 most likely orbiting on a highly eccentric orbit with e ~ 0.9, Rp ~ 5 kpc, Ra=110 kpc

Conclusion on Pal4 and Pal 14

- The shape of the present-day stellar MF probes the birth place of clusters and their orbits (e=0.9, Rp=5 kpc) in the Galactic environment. e<0.8 and Rp>10 kpc is ruled out.
- The high degree of **primordial mass segregation seems to be unavoidable** in every scenario we considered for Pal 4.
- Other scenarios such as accretion from a satellite galaxy

The Metallicity- and Density-Dependent IMF in the Globular Clusters in M31



The Mass Function (MF) and the mass-to-light ratio (M/L) evolve at early stages and also during the cluster evolution as the stars are removed from the system through stellar and dynamical evolution. (Vesperini & Heggie 1997; Baumgardt & Makino 2003, Zonoozi et al. 2011, 2014, 2017, Haghi et al. 2015, Bianchini et al. 2017,).

The IMF-dependence of M/L

The Stellar Evolution raises the M/L ratio of a cluster with time The Dynamical Evolution leads to a decrease in the M/L ratio



M/L ratio and [Fe/H]



M/L – [Fe/H] correlation of GC population in M31



The Stellar Evolution raises the M/L ratio of a cluster with time The Dynamical Evolution leads to a decrease in the M/L ratio

How one can reduce the M/L?

Adding stars with low M/L
 (High-mass) stars
 IMF variation: a shallow IMF

Removing stars with high M/L (low-mass) stars:

> Enhanced dynamical evolution: mass segregation



(Kruijssen & Mieske, 2009)

The canonical Kroupa IMF: Dynamical evolution and the M/L ratios



Dynamical evolution leads to a decrease in the M/L ratios, but can not explain the observed anti-correlation. (Zonoozi et al. 2016)

Density and metallicity dependence of IMF: **Top-heavy IMF**

The IMF may depends on the star formation enviroment (density and metallicity of star-forming cores), leading to a "top-heavy IMF" with a larger population of massive stars compared to the canonical IMF.

(Dabringhausen et al. 2009, 2010, 2012; Marks et al. 2012)

$$\alpha_3 = \begin{cases} +2.3, & x < -0.87, \\ -0.41 \times x + 1.94, & x \ge -0.87. \end{cases}$$

x = -0.14[Fe/H] + 0.99 log₁₀($\rho_{cl}/(10^{6}M_{\odot} \text{ pc}^{-3}))$

Incorporation of the Stellar/Dynamical evolution and top-heavy IMF can explain the correlation.



The effect of Metallicity- and Density-Dependent IMF on the Survival and Dissolution of Star Clusters

Is the stellar IMF Universal?



The stellar IMF

- Is the stellar IMF a universal probability distribution function?
- It is expected that the IMF varies and for example becomes top-heavy for high density and metal-poor star-forming regions
- For active galaxies with high SFRs, the top-heavy IMF is expected
- Kroupa & Weidner (2003) introduced integrated galactic IMF (IGIMF) theory to formulate the galaxy-wide IMF.



The IMF depends on environment

Observational evidences in UCDs and GCs show that the IMF is top-heavy in **metal-poor** and **dense** environment

Dabringhausen et al. 2009, 2010, 2012: Evidence from UCDs Marks et al. 2012 : Evidence from GCs Kroupa et al. 2013, Weidner & Kroupa 2013: Theoretical evidence

$$\xi(m) \propto m^{-\alpha} : \begin{cases} \alpha_1 = 1.35 , \quad 0.08 < \frac{m}{M_{\odot}} < 0.50 \\ \alpha_2 = 2.35 , \quad 0.50 < \frac{m}{M_{\odot}} < 1.00 \\ \alpha_3 , \quad 1.0 < \frac{m}{M_{\odot}} < 100.0 \end{cases}$$

Top-heavy IMF $\alpha_3 = \begin{cases} +2.3, & x < -0.87, \\ -0.41 \times x + 1.94, & x \ge -0.87. \end{cases}$

x = -0.14[Fe/H] + 0.99 log₁₀($\rho_{cl}/(10^6 M_{\odot} \text{ pc}^{-3}))$

Marks et al. (2012)

Indirect evidence for top-heavy IMF:

M/L – [Fe/H] correlation of GC population in M31

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The evolution of star clusters starting with a top-heavy IMF

N-body models: Initial conditions Top-heavy IMF

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 $(\alpha_3 = 1.5, 1.7, 1.9, 2.1, 2.3)$

Initial Mass- radius relation of Marks-Kroupa (2012)

$$\frac{r_{\rm h}}{\rm pc} = \sqrt[3]{\frac{3\left(M_{\rm ecl}/M_{\odot}\right)^{1-a}}{8\pi \times 10^{b}}} = 0.10^{+0.07}_{-0.04} \times \left(\frac{M_{\rm ecl}}{M_{\odot}}\right)^{0.13 \pm 0.04},$$

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Evolution of cluster mass and size



Evolution of cluster mass and size



Dissolution time



Minimum Survived mass of clusters vs. MF-slope



$$\begin{split} log_{10}(M^{min}_{surv}) &= A \; (\alpha_3)^{-\eta} + B, \\ \text{Haghi, Zonoozi et al 2020} \end{split}$$

where
$$A = 15.7 M_{\odot}$$
, $\eta = 6$ and $B = 4.5 M_{\odot}$.



$$F_{exp}(\alpha_3) = e(\alpha_3) + f$$

where $e = -16.7 \pm 1.7$ and $f = 51.3 \pm 3.3$