Constraining the star formation rate in the Solar neighborhood with star cluster

Bonatto & Bica, arXiv:1104.2182v1

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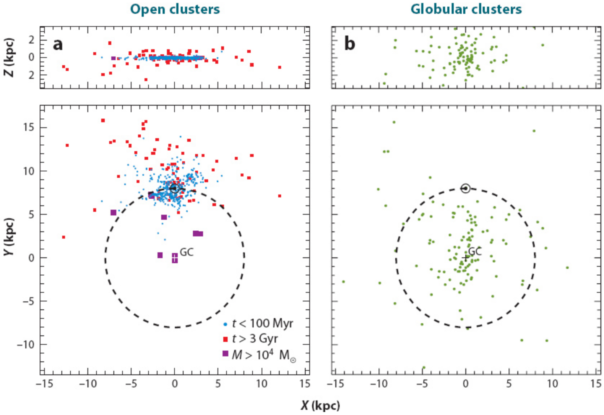
Outline

Star cluster dissolution and destroy

- star cluster has limit lifetime
  - stellar evolution and limit star number
  - depends on the classification and location in the Milky Way
  - most star clusters hard to survive



Cont'd Star cluster dissolution and destroy

Facts and suggestions:

- Few clusters appear at the middle plane
  - Large destroy at the middle plane ?
  - The youngest clusters form here
- Few small mass clusters appear at inner solar orbit
  - Large destroy near Galactic center
  - Massive clusters (partial) survive
- Massive and old clusters (GCs) can be survived uniformly
  - Halo
  - Stronger self-bound

Classifications of clusters

- Open clusters (OCs)
  - confined to the Galactic plane
  - almost always found within spiral arms
  - a few hundred members (10^2 to 10^4 stars), relative sparse
  - no definite shape
  - large span of age, from 10^5 to 10^8 yrs
- Globular clusters (GCs)
  - move in the halo with large elliptical orbits of higher eccentricities
  - contain old stars, $\sim 10^6 \mathrm{M}_\odot$, metallicity poor
  - roughly spherical shape
  - 158 GCs confirmed so far: 10 to 20 are not sure
  - large time scale (age range 10^9 to 10^{10} yrs)
    - long evaporation and dissolution time
    - strong self-graviton

Cont'd Classifications of clusters

Another two types:

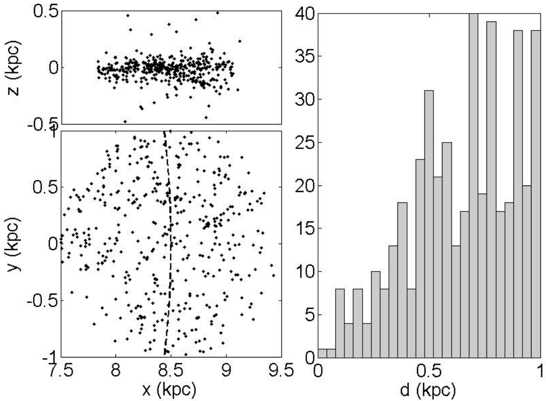
- Young massive clusters (YMCs)
  - age < 100 Myr
  - $M > 10^4 \mathrm{M}_\odot$
  - $\bar{m} > 5\mathrm{M}_\odot$
  - core density $\rho_c > 10^3 \mathrm{M}_\odot \mathrm{pc}^{-3}$ similar with GCs
- Embedded clusters (ECs)
  - partially or fully encased in the ISM, such as giant molecular clouds (GMCs)
  - less than $4 \sim 7\%$ of ECs survive to become clusters

Star Formation Rate (SFR)

- local SFR as the a function of time t:
    - Stars formed in clusters as the bottom line of SFR
    - Clusters as the tracer of SFR: need time (age of cluster as time of birth)
    - Can be simulated and then compared with observational constrains
    - $M_{\rm tot} = \int {\rm SFR}(t){\rm d}t$
    - local surface star formation rate $\sum_{\rm SFR}$
- SFR from observations
    - Combination of WEBDA, DAML02, and recent literatures
    - solar distance is limited in 1 kpc
    - including OCs, ECs, YMCs (describe later)

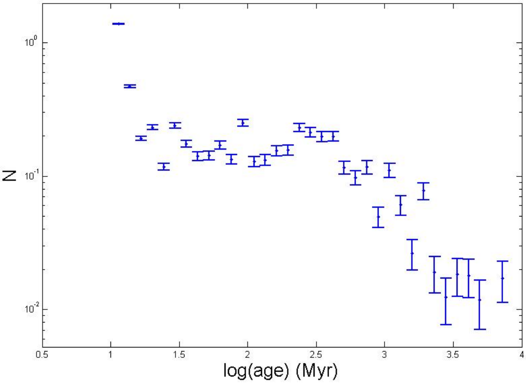
Sample

- 442 clusters as the sample
  - Combination of WEBDA, DAML02, and recent literatures
  - solar distance is limited in 1 kpc
  - including OCs, ECs, YMCs (describe later)
- ages up to 10^4 Myr



Age Distribution Function (ADF)

- ADF(τ)
  - Very steep trend
  - Very few old clusters
  - One star-burst feature around $\lg(\tau) = 2.5$
  - It's not simple power or exponential law



Mechanisms

- Stellar evolution and dynamical effects (dissolution)

1. Stellar evolution
    - Stellar winds and supernova ejecta
    - Kick out WDs, NS, and BHs
2. Tidal effects of the Galactic field
3. Shocks with spiral arms
4. Encounters with giant molecular clouds (GMCs)
5. Evaporation
6. Ejection

Total mass loss rate

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \sum_{p=1}^{6} (\frac{\mathrm{d}M}{\mathrm{d}t})_p \tag{1}$$

1. Mass-loss by stellar evolution

Define:

- Stellar evolutionary remaining mass fraction $\mu(t) = \frac{M(t)}{M_i}$
- Compact objects mass fraction μ_{BH}, μ_{NS} and μ_{WD}
- The mass fraction lost by stellar winds $1 - \mu(t)$

mass fraction

$$\mu_{ev}(t) = \mu(t) - f_{kick}^{BH}\mu_{BH}(t) - f_{kick}^{NS}\mu_{NS}(t) - f_{kick}^{WD}\mu_{WD}(t) \quad (2)$$

and

$$\mu_{lum}^{ev}(t) = \mu(t) - \mu_{BH}(t) - \mu_{NS}(t) - \mu_{WD}(t) \quad (3)$$

this process starts from $t > 10$ Myr (earlier ECs)

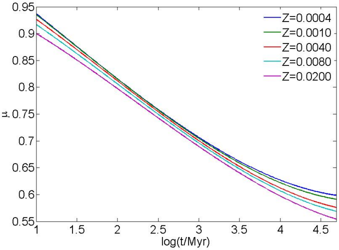
1. Mass loss rate of stellar evolution

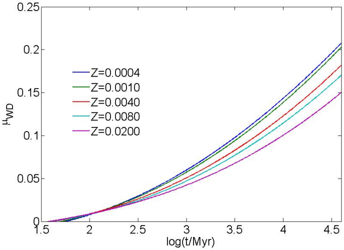
- Mass loss depends on abundance and on IMF
    - Assuming a Kroupa IMF
    - Using Hurley et al. (2000) evolutionary track
    - μ can be expressed as a 3rd order polynomials function of time

mass fraction

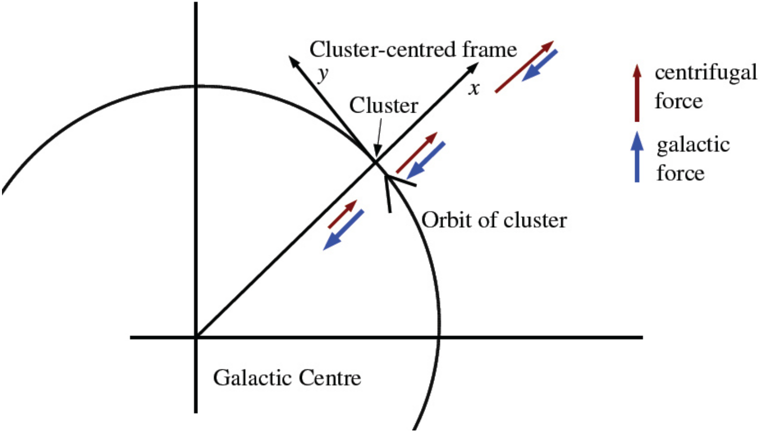
$$\mu(t;Z) = a_0 + a_1 x + a_2 x^2 + a_3 x^3$$

with $x = \lg(t/\mathrm{Myr})$

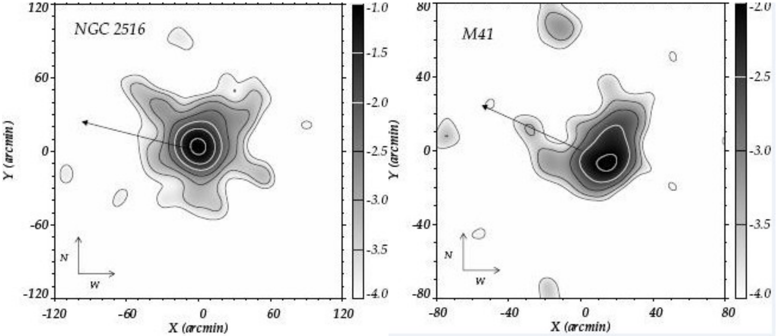




2. Tidal effects of the Galactic field



Cont'd Tidal effects of the Galactic field



$$t_{dis} = t_4 (M/10^4 M_\odot)^\gamma, \qquad (4)$$

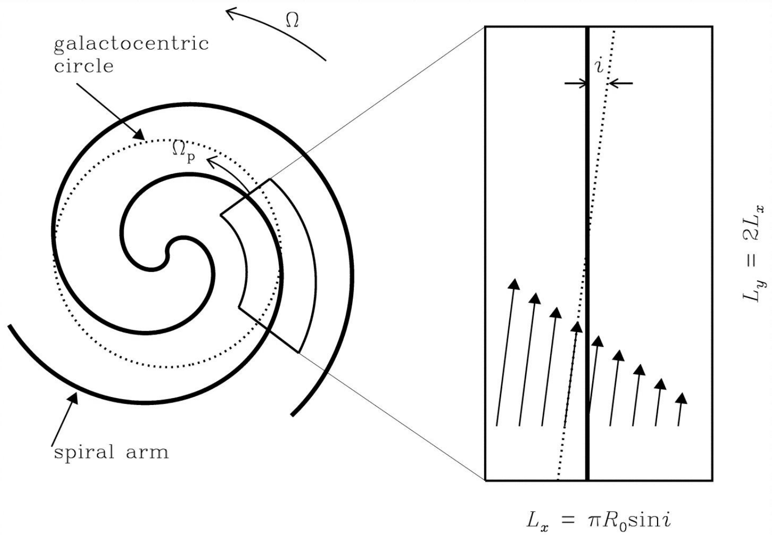
where t_0 depends on the environment and $\gamma = 0.62$ is derived by observation (Gieles et al. 2004)

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{tf} = -\frac{M(t)}{t_{dis}} = -\frac{(M/10^4 M_\odot)^{0.38}}{t_4/10^4} M_\odot Myr^{-1}. \qquad (5)$$

3. Shocks with spiral arms

- Mass loss due to the disk shocks
    - spiral arms lead to disk shocks
    - mass loss occur at moment the cluster crosses the spiral arm
- Assuming
    - spiral arms move with const. speed $\Omega_p = 25.9 \mathrm{kms}^{-1}\mathrm{kpc}^{-1}$
    - matter in the disk move with const. velocity $V_{disk} = 220\mathrm{kms}^{-1}$
    - the relative velocity between them V_{drift} depends on the location R
    - A shock wave passes with low V_{drift} has a large effect (large mass-loss)
- The most important effect appears at co-rotation radius
    - $R_{CR} = \frac{V_{disk}}{\Omega_p} \approx R_0$

Cont'd Shocks with spiral arms



Cont'd Shocks with spiral arms

Mass loss rate depends on half-mass radius

$$(dM/dt) \propto M/\rho_h \propto r_h^3 \tag{6}$$

$$t_{sp} \equiv -M/(dM/dt) \propto M/r_h^3 \tag{7}$$

The dissolution time

$$t_{sp} = 2 \times 10^4 (\frac{M}{10^4 \mathrm{M}_\odot})(\frac{3.75\mathrm{pc}}{r_h})^3 \mathrm{Myr} \tag{8}$$

Larsen (2004) fitted the radius of clusters in 18 spiral galaxies:

$$r_h = 3.75(M/10^4 \mathrm{M}_\odot)^\lambda \tag{9}$$

$$\Rightarrow t_{sp} = 2 \times 10^4 (M/10^4 \mathrm{M}_\odot)^{1-3\lambda} \tag{10}$$

Cont'd Shocks with spiral arms

Mass loss rate

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{sp} = -\frac{M}{t_{sp}} = -0.5\left(\frac{M(t)}{10^4\mathrm{M}_\odot}\right)^{3\lambda}\mathrm{M}_\odot\mathrm{Myr}^{-1} \qquad (11)$$

- Larsen (2004) found $\lambda \sim 0.1$
- ... and then mass loss rate $\propto M^{0.3}$ similar with tidal field ($M^{0.38}$)

4. Encounters with GMCs

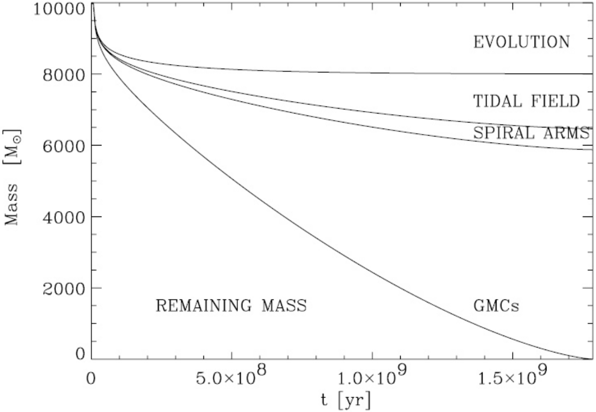
Mass loss rate

$$t_{GMC} = 2.0 \times 10^3 \left(\frac{M}{10^4 M_\odot}\right)\left(\frac{3.75pc}{r_h}\right)^3 Myr \qquad (12)$$

$$\left(\frac{d\mu}{dt}\right)_{GMC} = -5 \times 10^{-4} \frac{\mu^{0.3}}{(M_i/10^4 M_\odot)^{0.7}} \qquad (13)$$

This effect is larger 10 times than that of shocks by spiral arms for same mass of the cluster @ solar neighborhood

Cont'd Encounters with GMCs



- The mass evolution of a cluster of $10^4 M_\odot$ @ solar neighborhood.
- The mass loss due to 4 effects: Encounters with GMCs dominant them @ solar neighborhood.

5. Ejection & 6. evaporation

- Stars can also escape from a cluster by ejection or evaporation

Ejection

- A single star close encounter with another star
- A star gains excess velocity $v_* \gg v_{esc}$
- SNe explosion in a binary system
- Escape accidentally

Evaporation

- A series of more distant encounters
- Low stars gain more energy slowly (mass-segregation)
- $v_* \approx v_{esc}$
- Escape when they are in the outer part of the cluster

Cont'd Ejection and evaporation

Khalisi et al. (2007) found by N-body simulation:

$$\left(\frac{\mathrm{d}\mu}{\mathrm{d}t}\right)_{ej} = -\frac{1}{46}\frac{\bar{m}(G\mu)^{1/2}}{(M_i r_h^3)^{1/2}} \tag{14}$$

and

$$\left(\frac{\mathrm{d}\mu}{\mathrm{d}t}\right)_{ev} = -\frac{\ln(\gamma_c N)}{13.8}\frac{\bar{m}(G\mu)^{1/2}}{(M_i r_h^3)^{1/2}} \tag{15}$$

where $r_h = 3.75(M/10^4\mathrm{M}_\odot)^{0.1}$ and $\gamma_c = 0.11$ is the Coulomb factor used to express total cross section fraction

- If $10^2 < N < 10^4$ then
- $(\frac{\mathrm{d}\mu}{\mathrm{d}t})_{ev}/(\frac{\mathrm{d}\mu}{\mathrm{d}t})_{ej} \approx 10 \ldots 20$

Effects of different clusters

- GCs
  - Dense and massive: small effect of TF
  - Locating in halo: small effects of GMCs, shocks with spiral arms
  - Most old stars with small mass: steady mass loss by SE
  - The effect of EV ?
- OCs
  - Sparse members: easier EV and EJ
  - Locating in the disk: easier GMCs, shocks, and tidal effects
  - Relative young and massive stars: stronger SE

Cont'd Effects of different clusters

- ECs
  - $\bar{m} \sim 5 M_\odot$
  - The disruptive GMCs
  - Rapid stellar evolution
  - Low birth rate, $\sim 4\%$ of ECs can arrive at 100 Myr at solar neighborhood
- YMCs
  - (partially) survived from ECs phase
  - Most massive stars
  - SE has large effects
  - Relative small effects of TF, shocks, and EV

Evolutionary phases of a cluster

1. Phase 1: Embedded clusters survive
    - Clusters are born embedded within GMCs (70 - 90 % stars)
    - only visible at infrared wavelengths
    - Less than 4C7% of ECs survive emergence from GMCs
    - Encounter with GMCs and lost most mass
2. Phase 2: Stellar evolution in clusters
    - only a small fraction of stars reside in cluster currently
    - Mass loss by stellar winds and kick out of compact objects
    - Massive stars evolve firstly to decrease $\bar{m}$
    - Quasi-steady, last relative large time until dissolution of clusters
3. Phase 3: Stellar dynamical process and external influences
    - Tidal field, shocks by spiral arms
    - Encounter with new accidental GMCs
    - Ejection and evaporation

Simulating ADF

- Mass distribution
  - A IMCF $\mathrm{d}N/\mathrm{d}M_i \propto M_i^{-2}$ (Elmegreen 2008)
  - Mass range $[10\mathrm{M}_\odot, 7.5 \times 10^4\mathrm{M}_\odot]$
  - Assign mass as

$$M_i = \frac{M_{min}}{1 - n(1 - M_{min}/M_{max})} \tag{16}$$

  (n is uniform distr. $[0, 1]$)
- Solve above Eq. (1)
  - Evolution with time until the age t_A
  - Calculate remaining mass for each cluster $M(t_A)$
- Create ADF
  - only more than $100\mathrm{M}_\odot$ are accounted (completeness limit assuming)

Cont'd Simulating ADF

- The following steps are taken:
  1. Assume all stars form in clusters,

$$M_{tot} = \int \mathrm{SFR}(t)dt \tag{17}$$

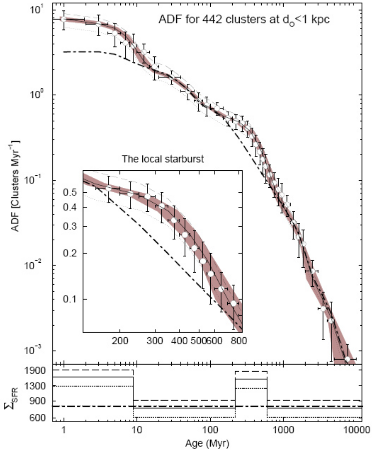
  2. Assign M_i for each cluster as above method
  3. Assign age t_A for each cluster randomly (corresponding $\mathrm{SFR}(t)$)
  4. Repeat Step 3 and 4 until total mass is M_{tot}
  5. Solve Eq. (1) from $t = 0$ to t_A using a 4th order Runge-Kutta method

$$M_j = M_j(t = t_A) \tag{18}$$

     for each cluster j
  6. Keep only $M_j(t_A) > 100\mathrm{M}_\odot$ to count

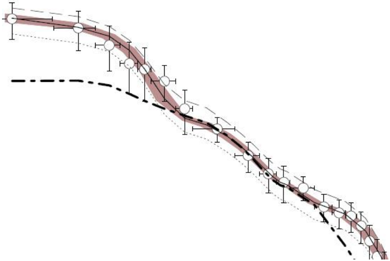
Constraining the local SFR

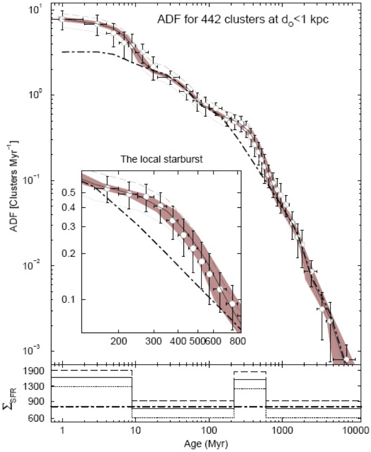
- Thick dashed dotted line
  - A constant SFR $2500\mathrm{M}_\odot\mathrm{Myr}^{-1}$
  - A large discrepancy at $t_A < 9\mathrm{Myr}$
  - Another at $200\mathrm{Myr} < t_A < 600\mathrm{Myr}$
- Solid line
  - A segmented SFR
  - $5040\mathrm{M}_\odot\mathrm{Myr}^{-1}$ at $t_A < 9\mathrm{Myr}$
  - $4800\mathrm{M}_\odot\mathrm{Myr}^{-1}$ at $200\mathrm{Myr} < t_A < 600\mathrm{Myr}$
  - $2400\mathrm{M}_\odot\mathrm{Myr}^{-1}$ elsewhere



Constraining the local SFR

- Dashed line and dotted line
- higher and lower 20% than matched SFR
  - much poorer match of ADF
- Adopt 20% as uncertainty of SFR





Discussion

- Consider above avg. SFR over all time
  - $\overline{\mathrm{SFR}} = (2500 \pm 500)\mathrm{M_\odot Myr^{-1}}$
  - $\overline{\sum_{\mathrm{SFR}}} = (790 \pm 160)\mathrm{M_\odot Myr^{-1} kpc^{-2}}$
- More than twice the value of Lamers et al. (2005)
- Consistent with that from ECs by Lada & Lada (2003)
- Lower $\sim 16\%$ than that of field stars by Miller & Scalo (1979)
- In simulations:
  - $\sim 3.3 \times 10^5$ clusters are created ($d < 1$ kpc)
  - $(91.2 \pm 2.7)\%$ destructure at first 10 Myr

Summary

- Archive a catalogue of clusters with $d < 1$ kpc
  - including OCs and ECs
  - no YMCs or GCs in this region
- A significant ADF built with 442 local clusters
  - with Poison errors
  - from 1 Myr to 10^4 Myr in log scale
- Summarize several different mechanisms of mass loss
  - SE, TF, shocks, GMCs, EV, and EJ for different types of clusters
  - Mass loss rate equation

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \sum_{p=1}^{6} (\frac{\mathrm{d}M(t)}{\mathrm{d}t})_p. \tag{19}$$

Cont'd Summary

- Comparison between observed and simulated ADFs
- Best match is non-const. SFR
  - with enhanced rates for two time regions
  - so-called local star-burst: 200 - 600 Myr ago
  - recent formation is twice avg. SFR: age < 9 Myr
- Const. SFR cannot produce enough excess ADF at those two positions

Cont'd Summary

- Non-const. SFR produces better ADF
  - A segmented SFR (4 pieces) matches very well
  - Determine the local avg. SFR $\overline{\mathrm{SFR}} = (2500 \pm 500)\mathrm{M}_{\odot}\mathrm{Myr}^{-1}$ and $\overline{\sum_{\mathrm{SFR}}} = (790 \pm 160)\mathrm{M}_{\odot}\mathrm{Myr}^{-1}\mathrm{kpc}^{-2}$
- $91.2 \pm 2.7\%$ clusters dissolve within first 10 Myr
  - that is consistent with the rate of ECs dissolution (Lada & Lada 2003)
  - implies all of dissolved clusters are ECs at very early time

Reference

Some details are from the following literature:

- Bonatto C. & Bica E., arXiv:1104.2182v1 [ADF]
- Lamers H. J. G. L. M. & Gieles M., A&A, 2006, 455, 17 [Clusters dissolution]
- Binney J. & Merrifield M. Galactic Astronomy [Basic picture]
- Lada C. & Lada E., ARA&A, 2003, 41, 57 [ECs]
- Portegies Zwart S. F. et al., ARA&A, 2010, 48, 431 [YMCs]
- Lamers H. J. G. L. M. et al., MNRAS, 2010, 409, 305 [Mass-loss]