Modern stellar dynamics, lecture 10: evolution of dense stellar systems

Eugene Vasiliev

Institute of Astronomy, Cambridge

Part III / MAst course, Winter 2022

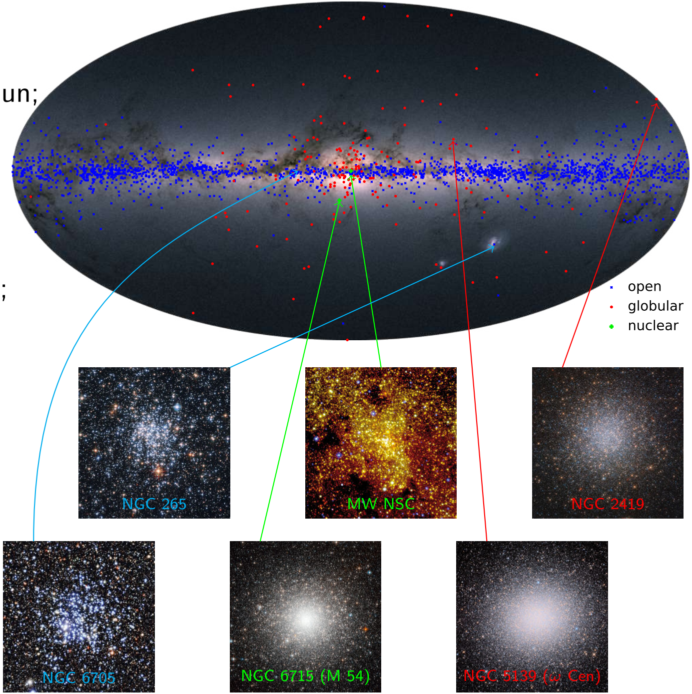
Setting the stage

Open clusters: $\sim 2\,000$ known
mostly within a few kpc from Sun;
age: 10^7 – few $\times 10^9$ yr;
[Fe/H]: ~ 0;
$N_\star$: $10^2 - 10^4$.

Globular clusters: ~ 160 across
the entire MW (up to 100 kpc);
age: $5 - 13$ Gyr;
[Fe/H]: $-2.5\,..\,0$;
$N_\star$: $10^4 - 10^6$.

Nuclear star clusters:
$0 - 1$ per galaxy;
age: spread from 10^7 to 10^{10};
[Fe/H]: $-1.5\,..\,0$;
$N_\star$: $10^5 - 10^8$.

Common feature: $T_{\rm rel} \lesssim$ age.



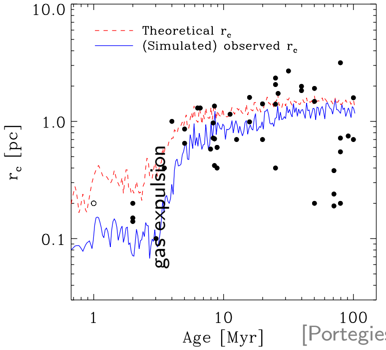
Early evolution of star clusters

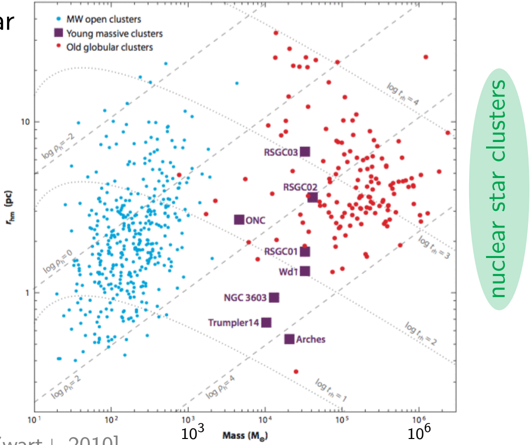
Star clusters are born embedded in a gas cloud, and the expulsion of gas during the first few Myr, supernova ejecta and stellar winds from short-lived massive stars may unbind the cluster altogether shortly after its birth.

Only a small fraction of star-forming regions survive the turbulent childhood to become open clusters with lifetimes $\gtrsim 10^8$ yr. It is natural to think that globular clusters were born in a similar way, but we don't know for sure.


R136 in LMC


Westerlund 1



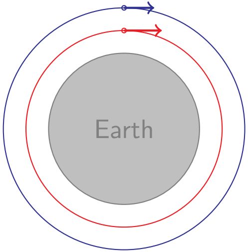


[Portegies Zwart+ 2010]

Negative heat capacity

virial equilibrium:

$$2K + W = 0$$



Self-gravitating systems have a unique property:
when you add energy, they cool down, and when you extract energy, they heat up!

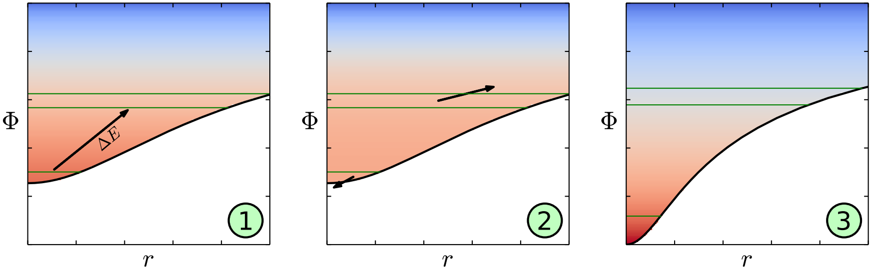
(example: a satellite losing energy to atmospheric drag moves to a lower orbit and thus increases its velocity).

This property ensures stability of thermonuclear fusion in stars: since the reaction rates are strongly sensitive to temperature, if too much energy is produced in the core, it expands and cools down, reducing the reaction rate back to equilibrium value. This negative feedback ensures that "normal" stars do not blow up, but fails in the cases when the pressure support is non-thermal (degenerate electron gas), e.g., during a helium flash or a Type Ia supernovae.

Gravothermal instability

In star clusters, however, the negative heat capacity, coupled with the energy exchange in stellar encounters, leads to a runaway process of "thermal polarization".

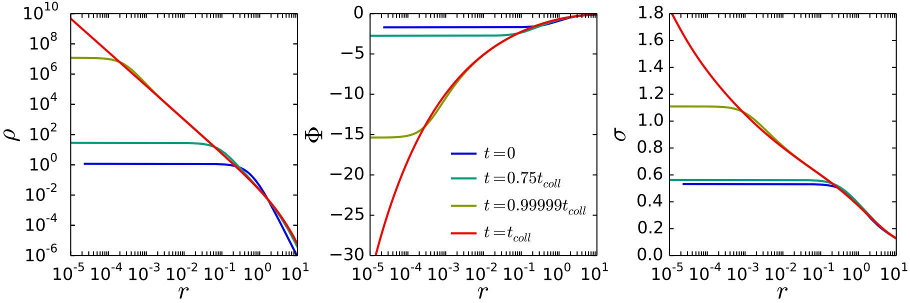
1. Inner parts of a stellar system are usually hotter (have higher σ), thus the two-body relaxation transfers energy from inside out.
2. The inner parts thus sink to a lower energy level, but because of virial equilibrium, this increases both the kinetic energy K and the absolute value of the potential energy $|W|$.
3. The density increases in the centre and decreases in the halo; the potential well becomes deeper, and the temperature contrast between the core and the halo grows.



Core collapse

Left to their own devices, star clusters undergo a runaway core collapse, achieving infinite central density and temperature in a finite time ($t_{\rm coll} \simeq 15.4\, T_{\rm rel,half-mass}$ for a Plummer sphere [Cohn 1980]). The asymptotic density profile is $\rho \propto r^{-2.23}$ (steeper than in the isothermal model, thus the temperature in the centre is higher and the energy flux is directed outward), and the end result is independent of initial conditions (at least in the central self-similar region).

The fundamental reason for this thermodynamical instability is that there is no maximum-entropy state in self-gravitating systems (it can grow without limits).

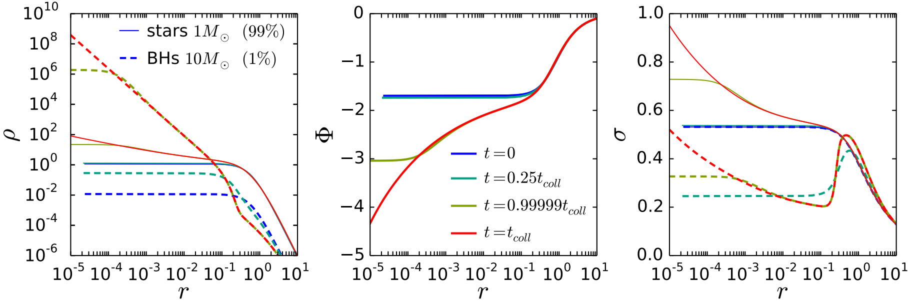


Mass segregation

In a multi-component stellar system, heavier stars experience dynamical friction and gradually concentrate in the central region (equivalently, the tendency towards equipartition of kinetic energy decreases their σ and makes them sink deeper in the potential well). This mass segregation might be imprinted already during the formation of the cluster, otherwise it sets on already in the early stages of evolution.

Because the contribution of each component to the total diffusion coefficient (relaxation rate) scales with the stellar mass $m_\star$, the heavy objects eventually start to dominate the relaxation rate even if they are much less numerous overall.

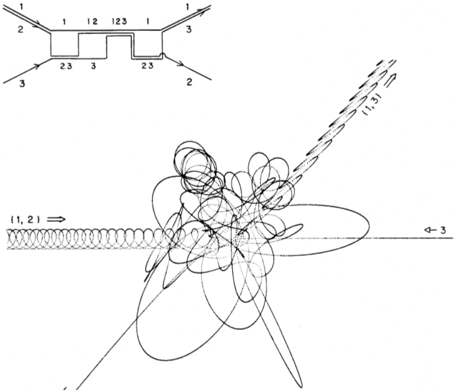
From that point on, the evolution of the heavy species proceeds towards the core collapse in the same way as in a single-component system, but the collapse occurs much sooner.



Binary stars and three-body interactions

The Fokker–Planck equation accounts only for pairwise encounters between stars. However, as the density gets higher, triple encounters also become significant. Such interactions are usually chaotic, but their outcomes can be studied in a statistical sense. One important process is the dynamical formation of binaries: among three incoming stars, two end up on a bound orbit, and the third carries away energy excess.

Another important class of triple encounters is between binaries and single stars. If the scattering is strong ($r_{\min} \lesssim G\,M/v_\infty^2$), these can have two possible outcomes: either the binary gets disrupted, or conversely, one of the stars (not necessarily the incoming single star, but usually the lightest one) is ejected with velocity $\sim v_{\rm bin}$, and the binary gets "harder" (more tightly bound). The rule of thumb [Heggie 1975] follows the general thermodynamics principle: "soft" binaries ($v_{\rm bin} \lesssim \sigma$, i.e., "colder" than the rest of the system) tend to be disrupted, while "hard" binaries get harder and hence hotter, transferring their energy to the field stars.



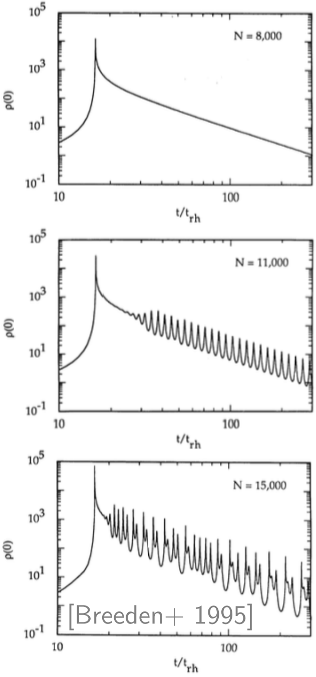
an example of 3-body exchange interaction [Hut & Bahcall 1983]

Post-collapse evolution and gravothermal oscillations

Binaries, whether primordial or dynamically formed in triple encounters, act as an energy source for the cluster and eventually halt the core collapse. The energy generated in the core is then pumped into the halo, causing its expansion.

However, if the core collapse reaches a very deep stage (for high enough $N \gtrsim 10^4$), the expansion is so rapid that it overshoots, the core cools too much and begins to collapse again. For even higher N, the process becomes chaotic (even with fully deterministic energy production!).

Another, more stochastic reason for oscillations is that once in a while a three-body scattering interatcion is so strong that both the single star and the binary attain recoil velocities greater than the escape speed from the cluster core, and thus the core loses its source of energy. Then another round of collapse sets in, and the core shrinks again until a new hard binary is formed. Either way, the post-collapse evolution is punctuated by gravothermal oscillations [Bettwieser & Sugimoto 1984; Heggie 1985; Cohn+ 1988; Makino 1996].



[Breeden+ 1995]

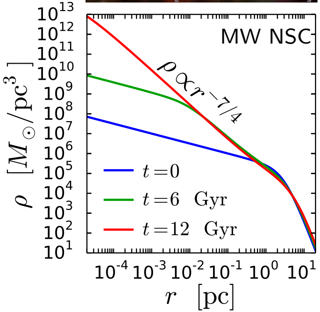
Formation and impact of a central massive black hole

Another possible outcome of a core collapse is a runaway onset of stellar collisions, creating a supermassive star that eventually turns into a large black hole ($\gtrsim 10^3\, M_\odot$). Supermassive black holes with $M \gtrsim 10^5\, M_\odot$ are found in many (though not all) nuclear star clusters, while intermediate-mass (10^2 to $10^5\, M_\odot$) black holes have been conjectured to exist in some globular clusters, but so far there is no indisputable evidence for them.

A black hole dominates the gravitational potential in its vicinity, thus stars sinking deeper in the potential well become hotter and transfer energy outward, as in a core-collapsing system. But the density cusp that forms around a black hole is shallower, $\rho \propto r^{-7/4}$ [Bahcall & Wolf 1976].


[credit: NASA]

Black holes tidally disrupt stars that come too close to them – in a typical galaxy, at a rate $10^{-4}\,\mathrm{yr}^{-1}$; a few dozen of tidal disruption events have been observed already.

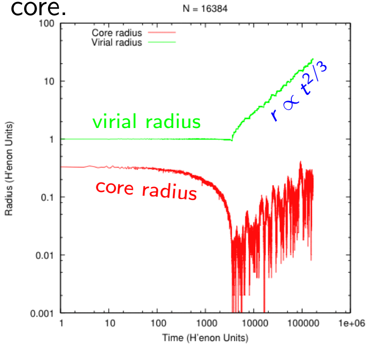


Since the stars removed from the system have very high negative energy (much higher than a typical star), the energy per star in the remaining system decreases in magnitude, again leading to the expansion of the cluster.

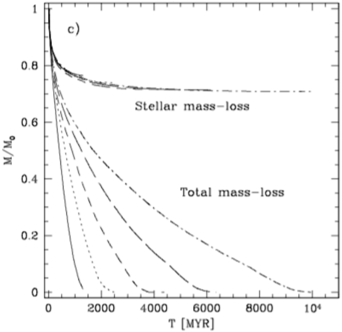
Balanced evolution, mass loss, and eventual dissolution

Importantly, the rate of energy production in the cluster centre ("burning" of binaries or tidal disruptions around a black hole) is determined by the capacity of the outer parts of the cluster ("halo") to transport and absorb the heat flux [Hénon 1975] – much like the stable thermonuclear burning in stars.

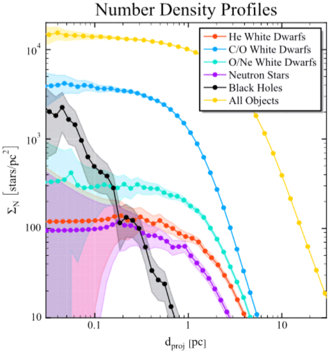
At this stage, there is still no true thermal equilibrium – rather, a self-similar expansion coupled with mass loss to galactic tides eventually leads to dissolution of the cluster. Due to mass segregation, low-mass stars escape from the outskirts more readily, and stellar remnants (white dwarfs, neutron stars and black holes) are concentrated in the core.



[credit: D.Heggie]



[Baumgardt & Makino 2003]



[Rodriguez+ 2022]

Physical collisions and formation of exotic objects

Distance of closest approach in a two-body encounter (Lecture 9):

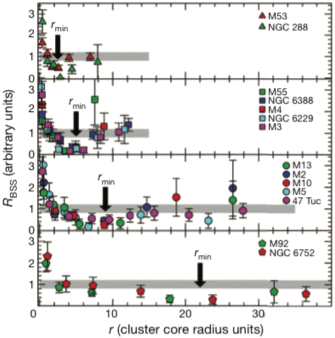
$$r_{\rm min} = \frac{b}{p+\sqrt{p^2+1}}, \text{ where } p = \frac{GM}{v^2\,b} \;\Rightarrow$$

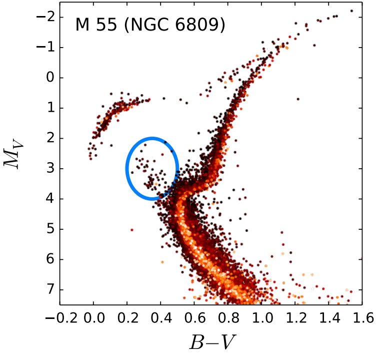
cross-section for stellar collisions is $\pi\, b^2\big|_{r_{\rm min}=r_\star} = \pi\, r_\star^2 \left(1+\dfrac{2GM}{v^2\,r_\star}\right)$.

Since the escape speed from stellar surface $v_{{\rm esc},\star} \equiv \sqrt{GM/r_\star}$ is typically much larger than the velocity dispersion of stars in a cluster, gravitational focusing is strong!

But this also means that stars are not destroyed in collisions, but rather merge and form massive stars exceeding the main-sequence turn-off for the given cluster age – hence the name "blue stragglers".

These objects are more massive than main-sequence turn-off stars, and concentrate in the cluster centre – their radial distribution defines a "dynamical clock" [Ferraro+ 2012].

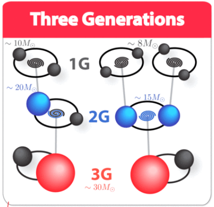




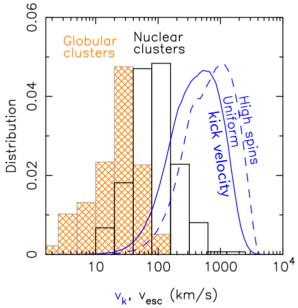
Stellar-mass black holes and gravitational-wave events

Dynamical formation and hardening of binaries, as well as eccentricity oscillations (Lidov–Kozai mechanism) in triple systems, provide fertile breeding ground for GW-induced BH mergers – star clusters might well be the main source of these events!

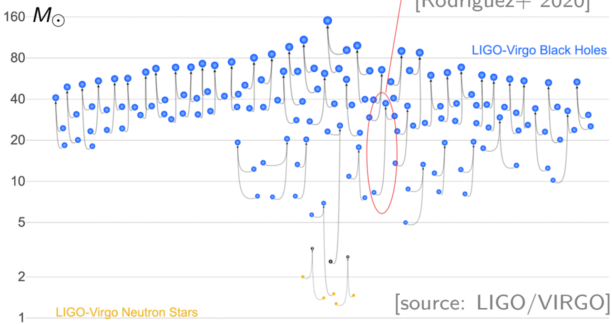
During a merger, asymmetries in GW emission produce a net velocity kick, and the remnant may escape from low-mass star clusters, but might be retained in the most massive globular clusters and especially galactic nuclei, forming "next-generation" binaries and leading to even more massive BH mergers [Antonini & Rasio 2016].



[Rodriguez+ 2020]

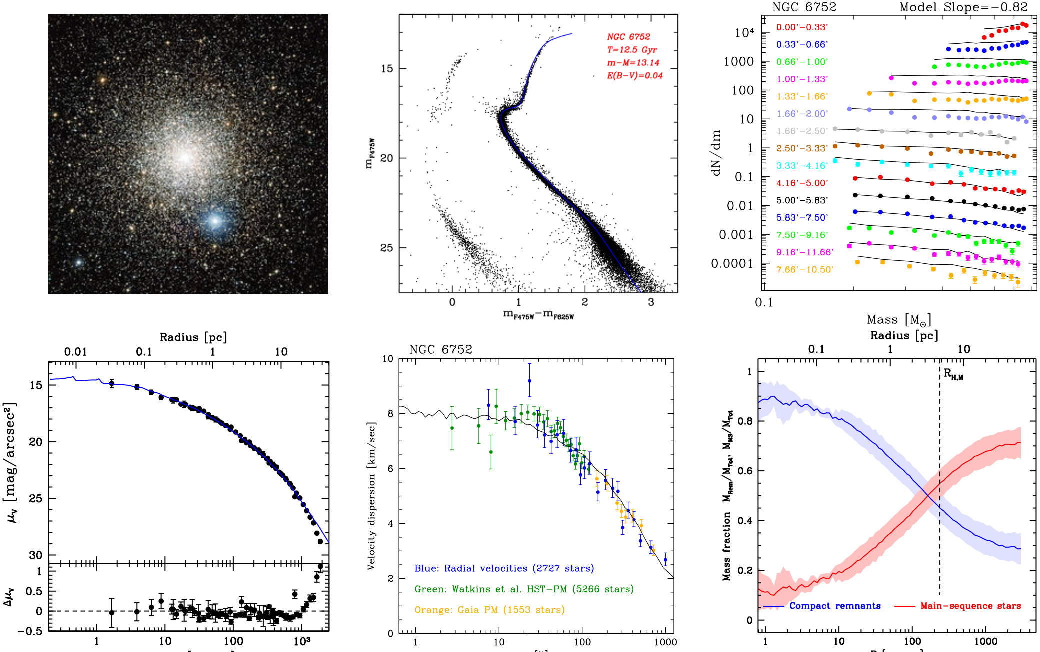


[Antonini & Rasio 2016]



[source: LIGO/VIRGO]

Example of an *N*-body fit of the globular cluster NGC 6752



[credit: H.Baumgardt]

Summary

- Evolution of dense stellar systems is primarily driven by gravitational two-body relaxation.
- The initial stage of mass segregation is followed by a runaway core collapse (gravothermal instability) driven by the most massive stars.
- The collapse is halted by hard stellar binaries, either primordial or produced dynamically in triple interactions at high density.
- Hard binaries or a central massive black hole act as an energy source for the cluster, much like thermonuclear fusion in a core of a star.
- Thermal expansion driven by this energy source, coupled to tidal stripping, eventually dissolves most clusters over timescales of $10^8 - 10^{10}$ yr.
- A multitude of exotic objects are formed in high-density environments.