Massive Stars in Interacting Binaries
ASP Conference Series, Vol. XXX, 2005
Nicole St-Louis & Tony Moffat eds.

Collisions Between Single Stars in Dense Clusters: Runaway Formation of a Massive Object

Marc Freitag

Astronomisches Rechen-Institut, Heidelberg, Germany

M. Atakan Gürkan and Frederic A. Rasio

Department of Physics and Astronomy, Northwestern University, USA

Abstract. Using Monte Carlo codes, we follow the collisional evolution of clusters in a variety of scenarios. We consider the conditions under which a cluster of main sequence stars may undergo rapid core collapse due to mass segregation, thus entering a phase of runaway collisions, forming a very massive star (VMS, $M_* > 1000\,\mathrm{M}_\odot$) through repeated collisions between single stars. Although collisional mass loss is accounted for realistically, we find that a VMS forms even in proto-galactic nuclei models with a high velocity dispersion (many $100\,\mathrm{km\,s^{-1}}$). Such a VMS may be a progenitor for an intermediate-mass black hole ($M_\bullet \geq 100\,\mathrm{M}_\odot$). In contrast, in galactic nuclei hosting a central massive black hole, collisions are found to be disruptive. The stars which are subject to collisions are progressively ground down by high-velocity collisions and a merger sequence appears impossible.

1. Introduction

In a stellar cluster, if the velocity dispersion is smaller than about $300\,\mathrm{km\,s^{-1}}$, the collision cross section is dominated by gravitational focusing. Under these conditions the (local) collision time, i.e., the average time after which all stars have experienced one collision, is given by

$$t_{\mathrm{coll}} \simeq 2.1 \times 10^{12}\,\mathrm{yr}\,\frac{10^6\,\mathrm{pc}^{-3}}{n}\,\frac{\sigma_v}{30\,\mathrm{km\,s^{-1}}}\,\frac{\mathrm{R}_\odot}{R_*}\,\frac{\mathrm{M}_\odot}{M_*}, \tag{1}$$

where n is the stellar density, σ_v the 1D velocity dispersion, and R_* and M_* are the typical values of the radius and the mass of a star, respectively. In view of this relation, one may think that direct collisions never play a role in cluster dynamics unless they are mediated by binary interactions, in which case the cross section is larger by a factor a/R_* where a is the typical binary separation. The role of binaries in cluster dynamics is presented by Fregeau, McMillan and Portegies-Zwart in these proceedings. In contrast, here we focus on two cases in which the collisions between single stars are likely to play an important role: (1) fast core collapse followed by runaway collisions in young dense clusters and (2) stellar dynamics in the vicinity of a massive black hole (MBH) at the center of a galaxy. In case (1), if there are no primordial binaries, the merger sequence is likely to start before the first binary forms dynamically through 3-body interactions (Freitag, Gürkan, & Rasio 2004); furthermore, primordial binaries probably foster collisions rather than preventing them by stalling the core collapse. In case (2), interaction rate peaks in the most central parts where densities exceed $10^7\,\mathrm{pc}^{-3}$. However, at this location owing to the MBH's presence, the velocity dispersion is also very high; as a result, most binaries are soft and should be dynamically dissociated.

To simulate the evolution of stellar clusters containing a large number of stars over time scales comparable to the relaxation (or collision) time, we use two Monte Carlo (MC) codes based on the pioneering ideas of Hénon (1971b,a). These codes are described in detail in the literature (Joshi et al. 2000, 2001; Freitag & Benz 2001, 2002). The MC method assumes that the cluster is spherical, in dynamical equilibrium and that 2-body relaxation can be treated in the Fokker-Planck approximation. The cluster is represented as a set of spherical shells ("particles") each of which may stand for a single star or a fixed number of stars which share the same orbital and stellar properties[1]. Typical particle numbers used in the simulations range between 10^5 and 10^7. The stellar orbital motion is not followed explicitly; instead one tracks the long-term evolution of orbits (and stellar properties) subject to relaxation, direct stellar collisions, stellar evolution and possibly interactions with a central MBH. Even though the effect of binaries may be accounted for in the MC method (Fregeau et al. 2003), here we consider only single stars. Various prescriptions can be used for the outcome of stellar collisions, ranging from sticky spheres to inter/extrapolation from a large database of SPH simulation results (Freitag & Benz 2004).

2. Runaway Formation of a Very Massive Star

We consider the evolution of young stellar clusters with a broad initial mass function (IMF). For all results presented here, we used the Salpeter IMF, $dN_*/dM_* \propto M_*^{-2.35}$ from 0.2 to $120\,\mathrm{M}_\odot$. There is no initial mass segregation.

We first studied the relaxation-driven core collapse to determine the conditions for it to occur while the most massive stars are still on the main sequence (MS), i.e. within $t_{\mathrm{MS}}(50-120\,\mathrm{M}_\odot) \approx 3\,\mathrm{Myr}$ (Gürkan, Freitag, & Rasio 2004). This condition arises because the mass loss during the giant phase and the subsequent supernova explosions would stop the core collapse and cause the cluster to expand. A key finding of our work is that, for a given cluster structure and a "reasonable" IMF (neither too flat or too steep), the core collapse time, t_{cc}, is simply proportional to the initial central relaxation time, where the proportionality constant depends on the ratio of the maximum to the average stellar mass, $t_{\mathrm{cc}} \simeq \alpha(\mu)\,t_{\mathrm{rc}}(0)$ with $\mu = M_{\mathrm{max}}/\langle M\rangle$. Furthermore, for $\mu > 50$, a regime reached by all realistic IMF, the dependency flattens to a constant value: $t_{\mathrm{cc}} \simeq 0.15\,t_{\mathrm{rc}}(0)$, independently of the cluster structure. With this we can predict that in any cluster with $t_{\mathrm{rc}}(0) \leq 20\,\mathrm{Myr}$, massive stars will form a dense collapsing core before they turn into remnants and should start colliding with each other. This condition for quick core collapse is plotted in Fig. 1. We see that, if clusters are born with relatively high concentration, a significant fraction of them lie in the proper region of parameter space.

---

[1] When one or a few particles start playing a special role, as in the collisional runaway process, using a a single particle to represent multiple stars is clearly questionable.

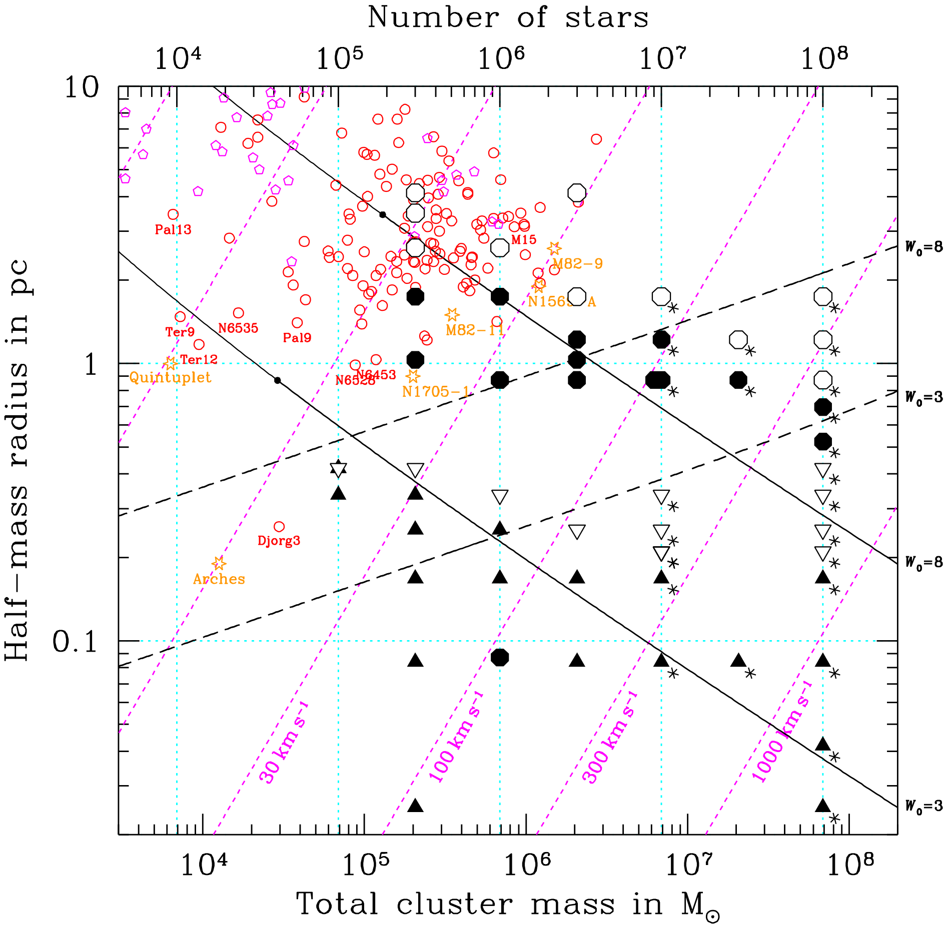

Figure 1. Conditions for quick core collapse and collisional runaway. Solid lines show the condition that the time for core collapse by relaxation is 3 Myr for King models with $W_0 = 3$ and $W_0 = 8$ and our standard IMF. Below this line, core collapse time is shorter. Dots on these lines indicate models that have initially 10^4 stars in their core, i.e. ~ 4 stars more massive than 50 $M_\odot$! Long-dashed lines indicate where the collision time for a 120 $M_\odot$ star is 3 Myr. Below this line, one may expect collisional effects to be important relative to relaxation. The approximate central 1D velocity dispersion is also indicated. Small symbols indicate the estimated conditions of a variety of observed clusters (globular or young); large symbols indicate the initial conditions of our MC simulations (triangles and round symbols for $W_0 = 3$ and 8, respectively). Open symbols are for runs which missed the runaway phase, and the filled symbols for those that experienced it. Asterisks denote simulations where the number of particles are smaller than the number of stars.

More recently we have explicitly considered the effects of collisions in a series of MC simulations (Freitag et al. 2004). As shown on Fig. 1, quick core collapse, followed by the runaway growth of a VMS through repeated mergers, happened in all cases for which we predicted $t_{\rm cc} < 3$ Myr, except when the number of particles is too low to have a critical number of massive stars initially present in the core. For clusters with large masses and small sizes, collisions themselves shorten the effective $t_{\rm cc}$ and we obtained runaway growth for larger clusters than predicted from the simple relaxational core collapse picture.

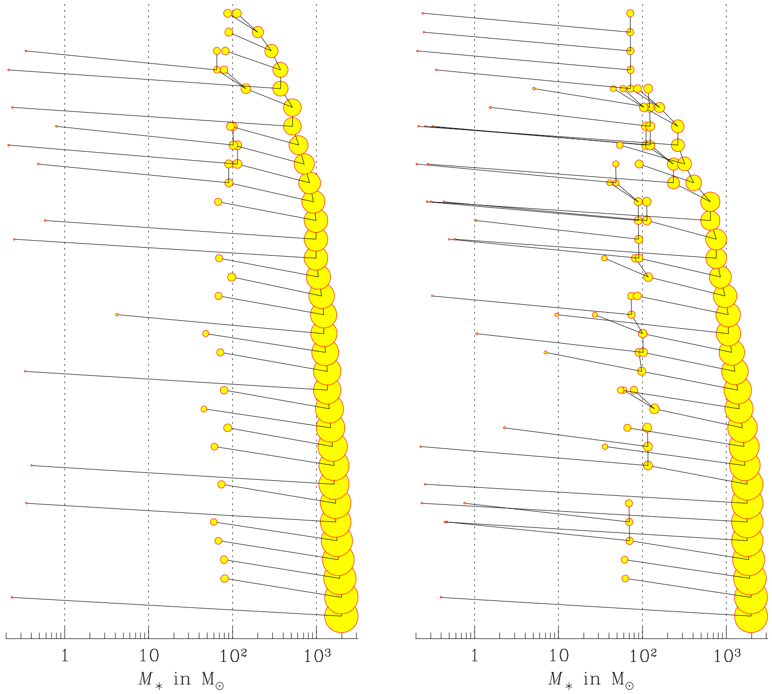

Figure 2. Merger trees for the simulation of clusters with $W_0 = 3$, $N_* = N_{\rm part} = 3 \times 10^5$. Left: $R_{\rm h} = 0.48\,{\rm pc}$. Right: $R_{\rm h} = 0.036\,{\rm pc}$. We follow the growth of the runaway star to $\sim 2000\,{\rm M}_\odot$. In case (a), the cluster is not initially collisional and most collisions occurs in deep collapse and feature stars of mass $70 - 120\,{\rm M}_\odot$ that have segregated to the center. In case (b), the cluster is initially collisional and most stars contributing to VMS growth have experienced earlier collisions.

Figures 2, 3 and 4 present a detailed look at the runaway sequences obtained in two simulations. In these cases we used the sticky sphere approximation which we checked to be fully justified when $\sigma_v \leq 300\,{\rm km\,s}^{-1}$. We note that, in most situations, a very important fraction of the mass accumulated in the VMS comes from the upper-most part of the IMF, $M_* \sim 100\,{\rm M}_\odot$, due to strong mass segregation. Another important finding is that, generally, the interval between mergers is much shorter than the thermal time scale of the VMS. Consequently, its structure is probably more extended and diffuse than a MS star, contrary to our assumption. Average growth rates are typically higher than $10^{-3}\,{\rm M}_\odot{\rm yr}^{-1}$.

Our results raise a number of open questions. One important planned extension of this work is to establish the role of primordial binaries. Most other uncertainties are connected with the final mass of the VMS and its fate. The vast majority of our simulations were artificially terminated when the VMS reached some high mass (typically $2000\,{\rm M}_\odot$) while the average time between mergers was still much shorter than the remaining MS lifetime. We think that, although they include collisional mass loss, our models lack the physics limiting the growth of

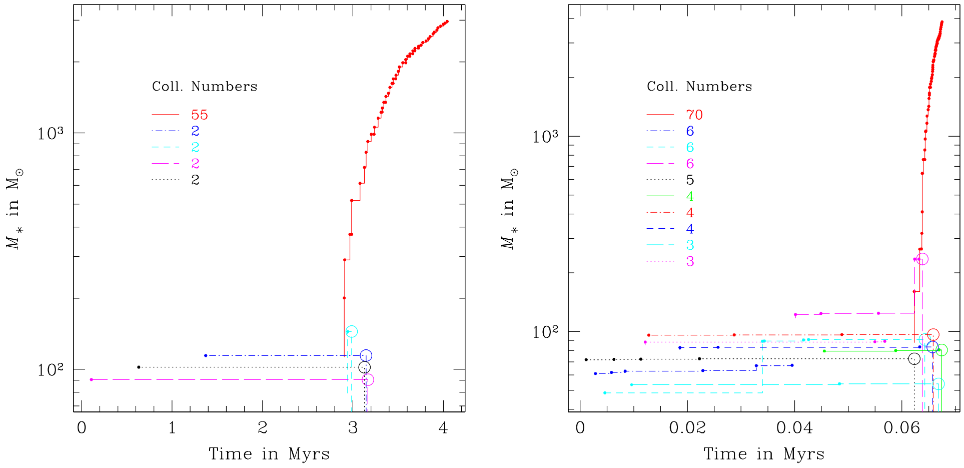

Figure 3. Collisions histories for the same simulations as in Fig. 2. Circles indicate that the particle has merged with the runaway object which grows very quickly at the moment of core collapse. For the smaller cluster, the collapse is so fast that it should be considered in the the frame of the formation process of the cluster.

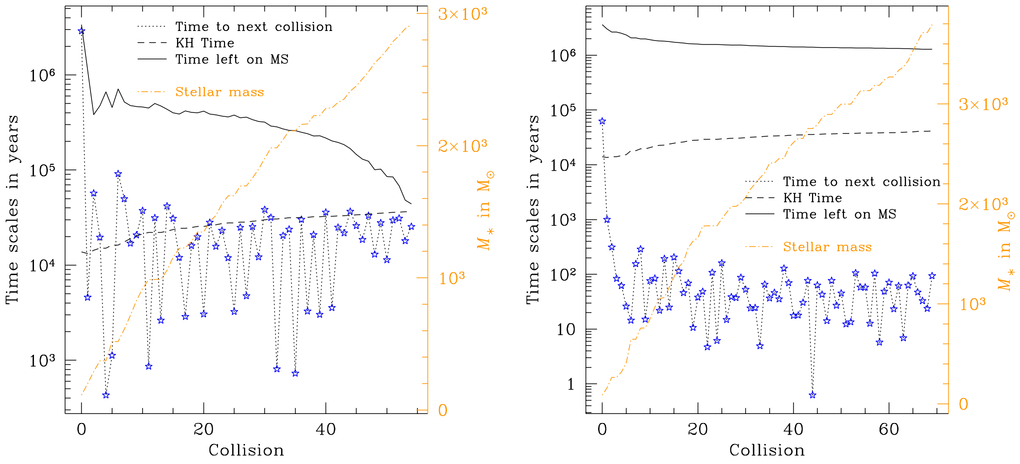

Figure 4. Time scales and mass evolution during the growth of the runaway star for the simulations of Fig. 2. We plot the time between successive collisions, an estimate of the (MS) Kelvin-Helmholtz time scale T_{KH}, the time left until exhaustion of the central hydrogen (left scale) and the mass of the star (right scale). T_{KH} is not considered during the simulations.

the VMS. Preliminary models assuming a fixed central VMS but accounting for depletion of “loss-cone” orbits show a saturation at a few $1000\,\mathrm{M}_\odot$. Another limiting mechanism may be that the VMS cannot radiate collision energy and swells until it becomes “transparent” to impacting stars. Whether the VMS will spawn an intermediate-mass BH is also uncertain because, once collisional growth levels off, strong stellar winds or pulsational instabilities may strongly reduce the VMS mass, unless the metallicity is very low. Finally we note that since the process occurs on a Myr time scale, it should be considered in the context of cluster formation, with account for the residual gas and pre-MS stars.

3. Collisions in Galactic Nuclei

The situation is completely different in galactic nuclei harboring a central MBH. Inside the radius of influence of the MBH, the stellar density probably follows a power-law cusp $n \propto R^{-\gamma}$ with $\gamma \simeq 1.5 - 2$ and the velocity dispersion raises like $\sigma_v \propto R^{-1/2}$. Hence, $t_{\rm coll} \propto R^{-(\gamma \pm 1/2)}$ and collisions should be effective very close to the MBH. But there the relative velocities are so high that partial or complete disruptions are more likely than mergers. Even a short sequence of mergers was never found in older MC galactic nucleus simulations such as shown in Fig. 5.

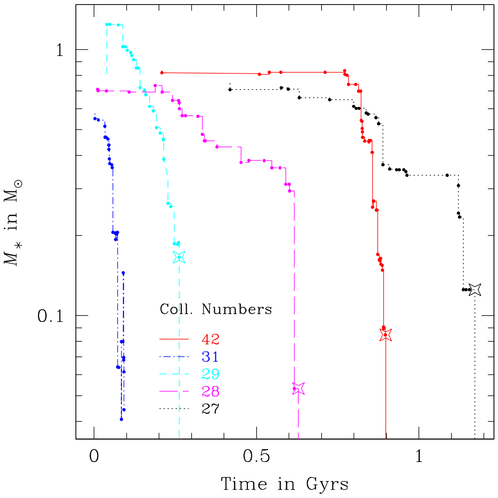

Figure 5. Collision sequences in the same simple model of the SgrA* cluster as used by Freitag (2003).

Acknowledgments. MF acknowledges support by the scheme SFB-439/A5 of the German Science Foundation (DFG). The work of AG and FR is supported by NASA ATP Grant NAG5-12044 and NSF Grant AST-0206276.

References

Fregeau, J. M., Gürkan, M. A., Joshi, K. J., & Rasio, F. A. 2003, ApJ, 593, 772
Freitag, M. 2003, ApJ Lett., 583, L21
Freitag, M. & Benz, W. 2001, A&A, 375, 711
—. 2002, A&A, 394, 345
—. 2004, submitted to MNRAS, astro-ph/0403621
Freitag, M., Gürkan, M. A., & Rasio, F. A. 2004, in preparation
Gürkan, M. A., Freitag, M., & Rasio, F. A. 2004, ApJ, 604
Hénon, M. 1971a, Ap&SS, 14, 151
—. 1971b, Ap&SS, 13, 284
Joshi, K. J., Nave, C. P., & Rasio, F. A. 2001, ApJ, 550, 691
Joshi, K. J., Rasio, F. A., & Portegies Zwart, S. 2000, ApJ, 540, 969