Monte Carlo Simulations of Dense Galactic Nuclei.

Marc Freitag
Observatoire de Genève, CH-1290 Sauverny, Switzerland

Willy Benz
Physikalisches Institut, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

1. Introduction

The presence of massive black holes (BHs) in the center of many galaxies appears as an inescapable conclusion of recent high-resolution observations. This fact revives much interest in the study of the joint evolution of the central BH and its surrounding stellar cluster. In particular, in systems with high stellar densities, bright accretion flares are bound to occur when stars are destroyed by the BH’s tidal forces or through collisions with other stars.

In the past few years, we have written a new code to simulate the evolution of the central star cluster (consisting of $10^6$–$10^9$ stars) over $10^9$–$10^{10}$ years. As disruptive events are more likely to occur in dense nuclei, we focused on such systems and devised a code that includes the most relevant physical processes, i.e., 2–body relaxation, tidal disruptions, stellar collisions, … (stellar evolution to be added in the next development stage). In our Monte Carlo (MC) scheme, based on the work by Hénon (1973), the cluster’s self-gravity as well as the BH’s growth are naturally coped for and no restriction applies to the stellar mass spectrum or the velocity distribution. The principal limitations of the method stem from its most powerful simplifying assumptions, namely that the stellar system is relaxed and that it obeys strict spherical symmetry. A complete description of this code is to be found in Freitag & Benz (2000a). It has recently been complemented with a module that uses the results of a large set of SPH (Smoothed Particle Hydrodynamics) simulations (Freitag & Benz 2000b) to implement stellar collisions with unprecedented realism.

2. Cluster Simulations with Stellar Collisions

Collisions have long been envisioned to play a key dynamical role in the evolution of dense galactic nuclei. Indeed, the early simulation works that included these events, showed that they can not only feed the central black hole with important amount of stellar gas but that they would also imprint the structure of the stellar cluster. Most noticeably, in these computations, the disruption of stars in the central regions prevent the formation of a steep $R^{-\alpha}$ density cusp with $\alpha \simeq 1.75$ but yielded a mild $\alpha \simeq 0.5$. Unfortunately, the way collisions were included in these previous papers cannot be claimed to be realistic. First, very simplistic recipes were used to determine the outcome of collisions; mainly
Figure 1. Accretion rate on the central BH. We assume instantaneous and complete accretion of the gas released in collisions (short dashes) or tidal disruptions (long dashes, including horizon crossing stars). **Panel (a):** Completely disruptive collisions (as in DS83). The dotted line shows a simulation without collisions. **Panel (b):** SPH-generated prescriptions for collisions. As in panel (a), all stars have initially $1 M_\odot$. **Panel (c):** Same as (b) but with mass spectrum $dN/M_* \propto M_*^{-2.35}$ over $0.35-17.3 M_\odot$ ($\langle M_* \rangle = 1 M_\odot$).

the assumption of complete disruption or some semi-analytical treatment similar to the one invented by Spitzer & Saslaw (1966). Furthermore, numerical schemes that perform a direct integration of the Fokker-Planck equation impose a fixed (relatively coarse) discretization of the mass spectrum. Consequently, even when partial disruptions or mergers are accounted for, the resulting stars are distributed over the existing mass classes in a quite unphysical way.

In the MC code, each particle represents a set of stars sharing the same physical properties. This particle-based approach, very similar to the N-body philosophy, allows arbitrary stellar masses and orbital properties. Thus, any prescription can be used to set the outcome of stellar collisions. To take the best advantage of this feature, we have computed a huge number ($\approx 14000$) of SPH simulations of collisions between MS stars. The outcome of any given collision is determined by interpolation into this database (Freitag & Benz 2000b).

To assess the influence of realistically treated collisions, we simulated nuclei models similar to those investigated by Duncan & Shapiro (1983, DS83). These are $W_0 = 8$ King models made of $3.6 \times 10^5$ $1 M_\odot$ stars with an initial central density of $\sim 7 \times 10^7$ pc$^{-3}$ and a $5 \times 10^4 M_\odot$ seed central black hole which is allowed to grow by accreting gas released in stellar collisions and tidal disruptions. Some of our results for these systems are depicted in Figs. 1 and 2. When we treat collisions the same way as DS83 did, either by neglecting them completely or, on the contrary, by assuming that every collision leads to complete disruption of both stars, we get results in good agreement with those of DS83. In particular, collisions completely dominate the BH’s feeding. However, when realistic (SPH-generated) prescriptions are used for the collisional outcome, most events, being grazing encounters, turn out to cause very limited mass loss and the growth rate is only slightly increased as compared to the simulation where collisions
Monte Carlo Simulations of Dense Galactic Nuclei.

Figure 2. Evolution of the spatial distribution of stellar masses. We show the stellar mass averaged over Lagrangian spheres containing 0.5 to 100% of the total cluster mass. Panel (a): Single mass model, same as in Fig. 1b. Panel (b): Extended mass spectrum, same as in Fig. 1c. Panel (c): Same as (b), without collisions.

are neglected. Also, a steep inner density cusp forms at late evolution stages with a slope closer to $\alpha = 1.75$ than to $\alpha = 0.5$. An intriguing feature of Fig. 1 is that, at late times, although the relative contribution of collisions and tidal disruptions is very different from one simulation to another, the total accretion rate is nearly the same in all cases, as if the cluster adjusts itself to ensure a given mass consumption rate, regardless of the details of disruptive processes. Further investigations should cast more light on this behaviour, reminiscent of the binary-driven post core-collapse evolution of globular clusters.

Fig. 2 illustrates how the stellar mass spectrum changes with time and position in the cluster as a result of mass segregation, collisions and tidal disruptions. Here the effect of collisions is more obvious than on the overall stellar structure. When no initial mass spectrum is present, they lead to a clear decrease of the average stellar mass ($\langle M_\ast \rangle$) in the center-most regions (after a short initial merging phase). With an extended initial mass spectrum, mass segregation leads to a quick rise of the central values of $\langle M_\ast \rangle$. At later stages, as central relative velocities close to the growing BH get higher and higher, collisions are more and more effective and prevent any further rise of $\langle M_\ast \rangle$.

References

Duncan, M. J., & Shapiro, S. L. 1983, ApJ, 268, 565
Freitag, M., & Benz, W. 2000a, “A new Monte Carlo code for star cluster simulations”, in preparation
Freitag, M., & Benz, W. 2000b, “A comprehensive set of collision simulations between main sequence stars”, in preparation
Hénon, M. 1973, in 3rd Advanced Course of the SSAA, Dynamical structure and evolution of stellar systems, ed. L. Martinet & M. Mayor, 183
Spitzer, L., Jr., & Saslaw, W. C. 1966, ApJ, 143, 400