Tides, Rotation or Anisotropy? Self-Consistent Nonspherical Models of Globular Clusters

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Outline

- GCs are usually considered as old, dense, tidally-limited, spherical stellar systems characterized by isotropic velocity dispersion tensor.
- Spherical King models [1], defined by a "lowered" Maxwellian distribution function, provide a good *zeroth-order* interpretation.
- Beyond the traditional paradigm for GCs: several key theoretical and observational issues require the construction of more advanced models.
- We developed a new analytical framework where fundamental physical ingredients, such as the three-dimensional external tidal field and internal rotation, which are usually neglected, are properly incorporated.

Theoretical Motivations

- **External tidal field:** External tidal field: energy truncation in King models is given by an *ad hoc* prescription, independent of the three-dimensional tidal field; therefore, a self-consistent approach is desired [2].
- **Internal rotation:** present-day GCs are only slowly rotating. But could their small observed flattening be due to such slow rotation? Furthermore, what about the past? The effects of angular momentum on the dynamical evolution of (quasi-relaxed) stellar systems are known to be important, but they are only partially understood! [3]
- **Anisotropy in the velocity space:** GCs are characterized by short relaxation times, so that their velocity dispersion tensor is expected to be isotropic, but:
  - less-relaxed objects may keep memory of their formation process and thus have a structure more similar to that of elliptical galaxies [4].
  - evolution in a (variable) tidal field may produce non-trivial kinematical signatures, expecially the outer parts of the cluster.

Observational Motivations

- New measurements of shapes and sizes of 116 Galactic GCs are available [5].
- Proper motions of thousands of stars have been measured in selected clusters (e.g. 47 Tuc, ω Cen).
- Structural parameters are available even for extragalactic clusters (e.g. in LMC, SMC, M31, NGC 5128).
- Existence of the "extra-tidal light", i.e. structures in the surface brightness profiles extending beyond what is prescribed by spherical King models, is frequently reported [6].

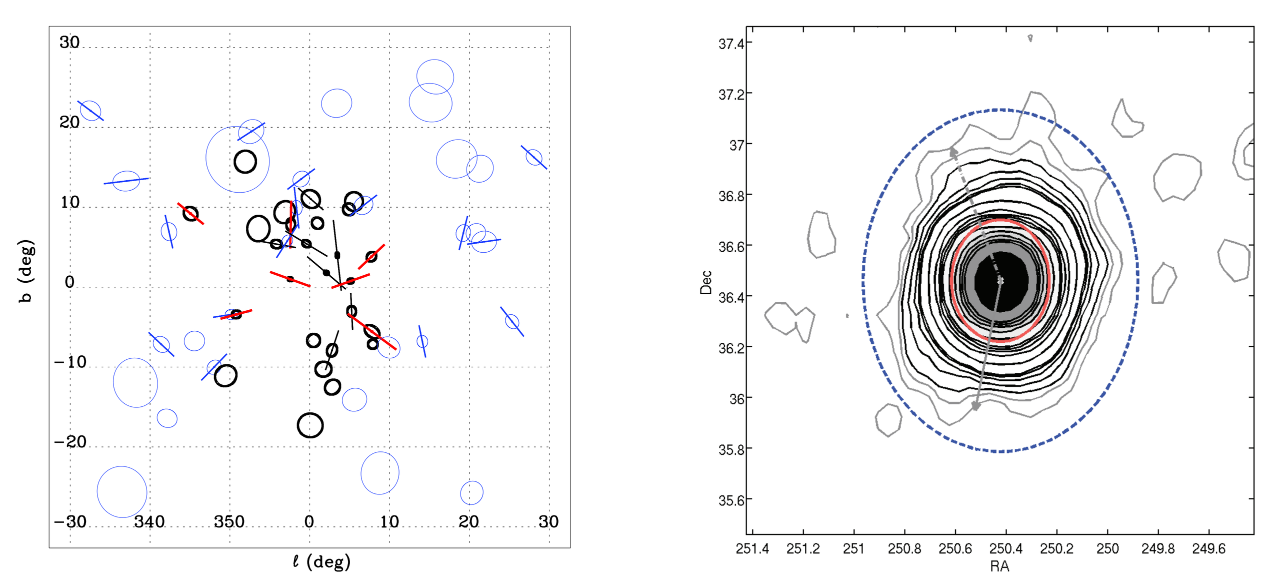

Figure 1: Left panel: Spatial distribution of 57 Galactic GCs, taken from [5]: for clusters flatter than average ($b/a < 0.87$) a segment with length proportional to the inverse axial ratio is drawn. Right panel: Isodensity contours for NGC 6205, taken from [6]: King radius is marked as red solid line, Jacobi radius as blue dashed line, the arrow points toward the Galactic Center.

1. Triaxial Tidal Models

See [8] for intrinsic and projected properties

Defined as a direct extension of spherical King models [1]:

$$f_K(H) = A[\exp(-aH) - \exp(-aH_0)] \qquad (1)$$

if $H \leq H_0$ and $f_K(H) = 0$ otherwise, where H is the Jacobi integral, evaluated within the "tidal approximation", the models are characterized by two dimensionless parameters:

$$\textbf{Concentration:} \quad \Psi \equiv \psi(\mathbf{0}) \qquad \textbf{Tidal strength:} \quad \epsilon \equiv \frac{\Omega^2}{4\pi G\rho_0} \qquad (2)$$

where ψ is the escape energy and Ω is the orbital velocity of the cluster.

- For a given value of the central potential well Ψ, there exists a (maximum) critical value for the tidal strength parameter. Two tidal regimes exist (i.e., models with small / significant departures from sphericity).
- The models studied in [2] correspond to our "critical" models, that is those for which the Roche lobes are completely filled and therefore the deviations from spherical symmetry are most significant.

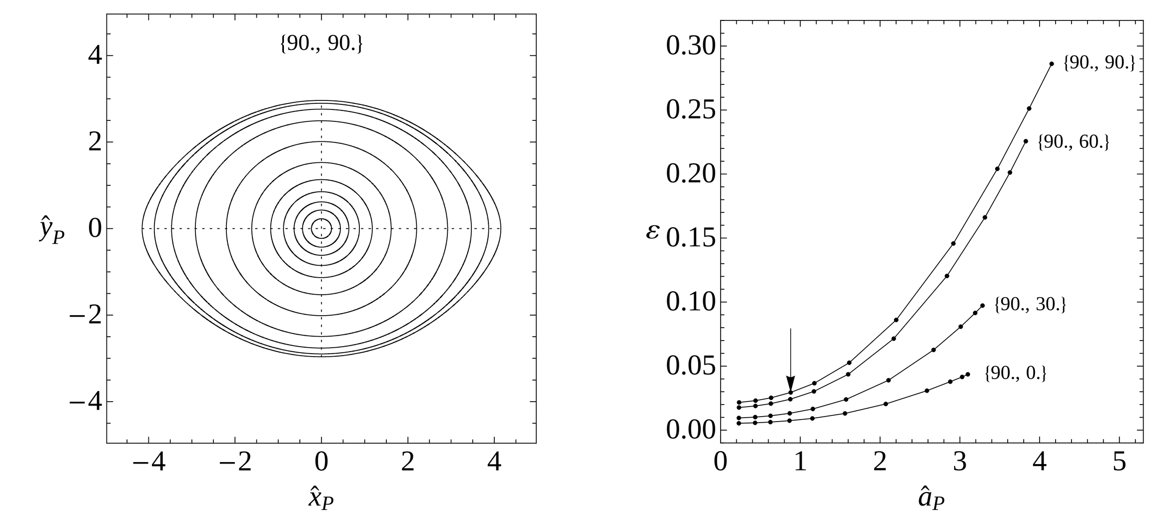

Figure 2: Left panel: Projection of a critical model ($\Psi = 2$ in a Keplerian host galaxy) along the lines of sight identified by $\{\theta, \phi\}$. Right panel: Ellipticity profiles of the projection along several lines of sight; dots represent the isophotes drawn in the left panel, for which the projected density $\Sigma/\Sigma_0 \in [0.9, 10^{-6}]$. The arrow indicates the half-light isophote.

2. Axisymmetric Rigidly Rotating Models

See [9] for intrinsic properties

Spherical King models [1] can be generalized to the case of internal rigid rotation by means of Eq. (1), in which, based on a general statistical mechanical argument, the integral H is defined as $H = E - \omega J_z$, with ω the angular velocity of the system. The parameter space is analogous to the one presented in the tidal case, with the role of ϵ played by:

$$\textbf{Rotation strength:} \quad \bar{\omega}^2 = \frac{9\omega^2}{4\pi G\rho_0} \qquad (3)$$

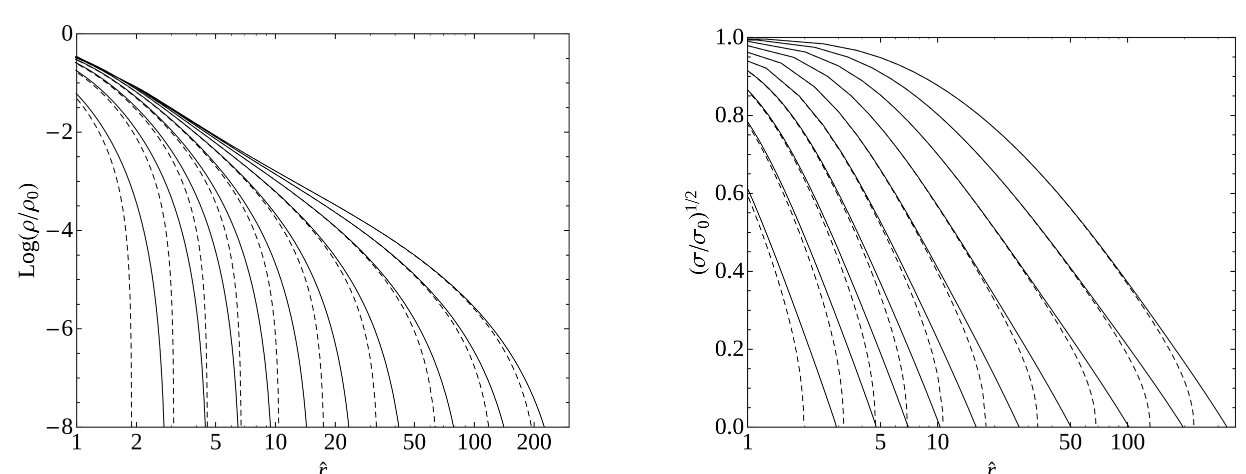

Figure 3: Left panel: Intrinsic density profiles for critical models along the $\hat{x}$-axis (solid) and the $\hat{z}$-axis (dashed), with $\Psi = 1, 2, ..., 10$ (from left to right). Right panel: Intrinsic velocity dispersion profiles for the models (with the same notation) displayed in the left panel.

3. Axisymmetric Differentially Rotating Models

See [9][10] for extensive description

New family of models defined by the following distribution function:

$$f_W(I) = A\exp(-aE_0)\{\exp[-a(I - E_0)] - 1 + a(I - E_0)\} \qquad (4)$$

if $E \leq E_0$ and $f_W(I) = 0$ otherwise, where the quantity:

$$I \equiv E - \frac{\omega J_z}{1 + bJ_z^{2c}} \qquad (5)$$

reduces to the Jacobi integral of a rigidly rotating system at small radii and tends to the single star energy at large radii.

- The resulting configurations are characterized by rigid rotation and isotropy in the center and tangential anisotropy at the boundary, where the rotation vanishes.
- Fast-rotating models tend to exhibit a toroidal core, the existence of which can be expressed in terms of a threshold value of the internal rotation.

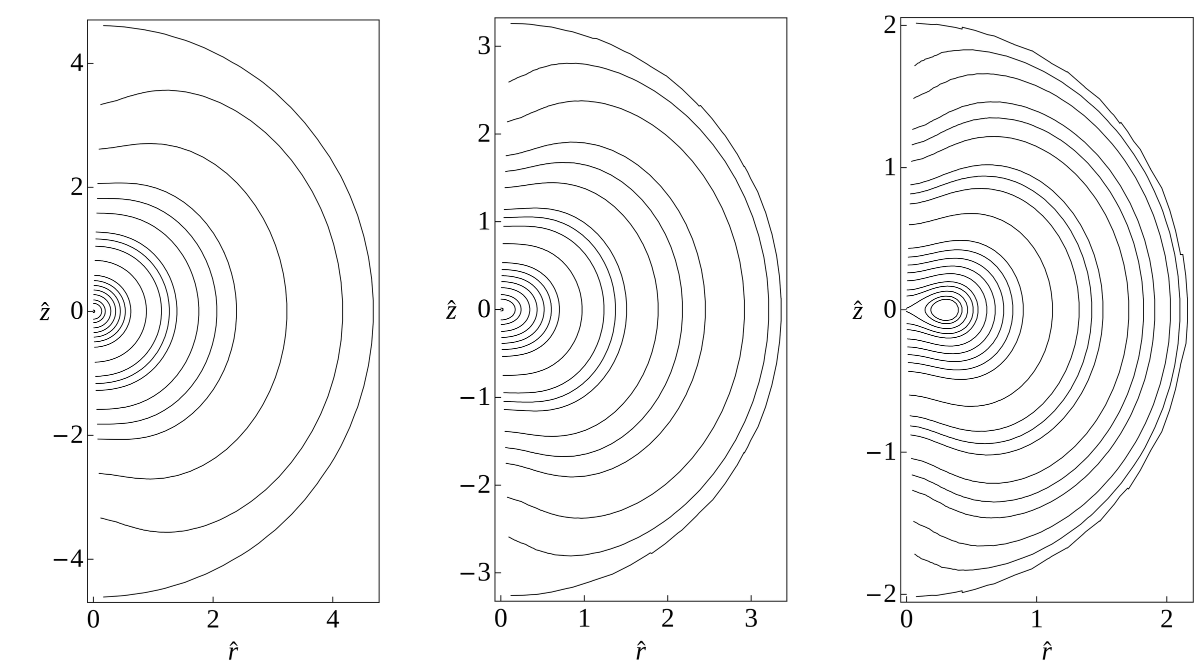

Figure 4: Meridional sections of the intrinsic isodensity surfaces of selected models, characterized by different values of the rotation strength at the center ($\bar{\omega} = 0.16, 0.33, 0.66$ from left to right; the other dimensionless parameters are set to be $\Psi = 2$ and $\bar{b} = c = 1$).

Conclusions and Future Developments

- Tidal models are a useful tool to clarify the nature of the "extra-tidal light".
- Within the new family of differentially rotating models, for application to GCs, models of interest should be those characterized by low values of the rotation strength parameter and quasi-spherical shape.
- The exploration of the dynamical evolution of these models by means of N-body simulations is currently carried out at Drexel University.
- Comparison with observational data is in progress at Università degli Studi di Milano, in order to investigate the physical origin of the deviations from spherical symmetry in selected Galactic GCs.

References

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Curious about the maths?

See [7] for details

The determination of the structure of the tidal and the rigidly rotating models described in Sects. 1 and 2 defines a singular perturbation problem. The differentially rotating models of Sect. 3, instead, are constructed by means of a spectral iteration method.

Background: Omega Centauri; Image Credit: NASA/JPL-Caltech/ NOAO/AURA/NSF

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