Triaxial Halos and Cusps

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Abstract. We present \(N\)–body models for triaxial elliptical galaxies or halos of galaxies, which are fully self–gravitating, have near constant axis ratio as a function of radius and a \(r^{-1}\) central density cusp. Preliminary investigation suggests the models are stable and orbit analysis shows no indication of chaotic orbits. The models provide a starting point for investigations into the evolution of triaxial figures of equilibrium, response of triaxial figures to central black holes, external perturbations and interactions.

There is strong evidence that at least some galaxies are triaxial (1,2,3). Models known as “perfect ellipsoids” have been developed to describe elliptical galaxies (4), but these have flat central cores, unlike those observed in real ellipticals. A problem of interest is whether it is possible to construct self–gravitating spheroids that are stationary, cuspy, and triaxial, and if so, how strong the cusp can be, and how strong the triaxiality may be. It is also interesting to explore how rapidly unstable figures evolve towards axisymmetry. Clearly in the limit of weak cusps and in the limit of weak triaxiality the figure evolution must either be very slow or non–existent. It has been conjectured that central singularities in the potential or density (5,6,7,8) introduce chaotic orbits that rapidly drive a secular evolution in figure shape. Open questions include whether non–regular orbits in non–integrable potentials are strongly chaotic or only “semi–stochastic”, and what fraction of phase space is occupied by irregular orbits (5,9).

Most investigations of these issues have used either rigid potentials or low resolution numerical models generated by cold collapse from initially triaxial conditions. We describe here a new method for generating self–gravitating triaxial spheroids with high numerical resolution. The models start off as spherical, with some initial density cusp, \(\rho(r) \propto r^{-\gamma}\). The models are realised as large \(N\) particle distributions, using a multi–mass realisation (10). The configurations are integrated using the SCF scheme (11). The large number of particles and the large number of dynamical times required makes this a problem particularly well suited for parallel implementations of the SCF method (12,13). Our code uses an adaptive Hermite integration scheme with variable multi–level timestepping (Sigurdsson et al; Mihos et al; in preparation).

To generate triaxial models, we squeeze the velocity ellipsoid using a simple iterative scheme; \(v_{y,z,i}(t) = v_{y,z,i}(t)(1 - \epsilon(dt, t, y, z))\). The choice of parameters is such that over many dynamical timescales the model settles to triaxial figure with ellipticities in the range 0.1–0.5, and triaxiality parameter \(T \sim 0.2 - 0.8\),
with the axis ratios close to constant with radius. The model discussed here has a density cusp $\gamma = -1$, intermediate axis $b = 0.85$ and minor axis $c = 0.7$, well approximated by a non-spherical Hernquist model. To check for long term stability, the model is then evolved for tens of dynamical times and the figure shape is compared with the initial shape. We see no evidence for secular evolution in axis ratios, or the slope of the inner density cusp. To investigate the intrinsic structure of the model we have generated surfaces of section for the major axis orbits. To do this, we freeze the potential generated by the distribution after the model has relaxed, and extract the SCF potential coefficients. These are then used to generate a rigid potential for integrating test particle orbits drawn either from the particles generating the density distribution in the model, or by placing test particles at chosen points in phase space. To check for the effect of numerical noise due to discreteness, we smoothed the final potential using the reflection symmetry of the distribution (a “quiet finish”, analogous to the “quiet start” technique advocated for numerical studies of stability). While the orbits in the unsmoothed potential are clearly noisier than in the smoothed potential there is no apparent qualitative change in orbit structure.

Figure 1 shows a surface of section for a set of particles in the x–y plane (the x–axis being the major axis, the y–axis the intermediate axis, by designation) with energy $E = -0.75$ (the particle energies range from 0 to $-1$). Figure 2 shows a second surface of section for $E = -0.9$. At the lower energy a large fraction of phase space is occupied by boxlets, with the resonant orbits contributing to the global figure shape as the box orbits break up. Some of the loops show signs of high order resonances. Neither figure shows any indication of chaotic orbits.

Clearly, moderately triaxial galaxies can exist with density cusps at least as strong as $r^{-1}$. It is possible that the technique we use to generate the models
“traps” a fraction of the particles in resonant orbits which serve to support the triaxial figure where other numerical techniques select for more axisymmetric figures. The particular model shown here is one of a family we have generated. Further analysis of the structure of the models is continuing and we are using the models for an investigation into the response of triaxial galaxies to the presence of central black holes (in preparation).

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