Basis-set expansion approach for modelling disrupting satellites and stellar streams

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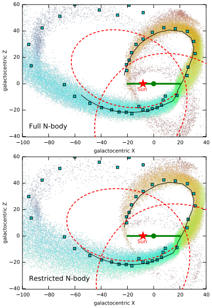
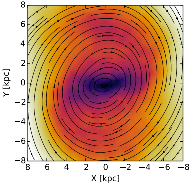


Simulation of the Sagittarius stream [Vasiliev+21]



Restricted *N*-body simulation of bar formation and large-scale elliptical distortion of the LMC disc due to its interaction with the Milky Way [in prep.]

fast

<table>
<tr><th></th><th>Particle spray
[Fardal+15; Chen+25]</th><th>CMC
[Rodriguez+22]</th><th>KRIOS, Raga
[Tep+25] [Vasiliev 15]</th><th colspan="2">Restricted N-body variants
[Vasiliev+21]</th><th colspan="2">conventional N-body simulations
[everybody]</th></tr>
<tr><td>Internal evolution of the satellite</td><td>none</td><td colspan="2">tides + Chandrasekhars's two-body relaxation (Hénon or Spitzer Monte Carlo approaches)</td><td colspan="4">collisionless evolution only (including mass loss due to tides)</td></tr>
<tr><td>Satellite potential representation</td><td>analytic profile (e.g. Plummer)</td><td>arbitrary spherical Φ_{sat}</td><td colspan="3">arbitrary non-spherical Φ_{sat}, using Multipole or Basis-Set expansions (aka Self-Consistent Field)</td><td colspan="2">conventional tree code</td></tr>
<tr><td>and its evolution</td><td>mass/radius fixed or their evolution prescribed manually</td><td colspan="3">Φ_{sat} updated once in a while (after a fraction of orbital period or relaxation time)</td><td colspan="3">Φ_{sat} updated every timestep of the particle integrator</td></tr>
<tr><td>Host galaxy representation</td><td colspan="6">fixed external potential Φ_{host}</td><td>live N-body system</td></tr>
<tr><td>Satellite trajectory</td><td colspan="5">rewind back from its present-day x,v in the host galaxy potential;
final sat's x,v in the simulation match the observed ones by construction</td><td colspan="2">present-day x,v may deviate from observed ones (need to iterate)</td></tr>
<tr><td>Dynamical friction</td><td colspan="5">optionally including Chandrasekhar's DF when rewinding sat's trajectory</td><td>may be added manually</td><td>appears naturally</td></tr>
<tr><td>Release of stream particles</td><td>at or around Lagrange points; seeding rate typically constant</td><td colspan="6">particles escape "naturally" with the rate determined by the internal evolution and tidal field</td></tr>
<tr><td>Trajectories of stream particles</td><td>any orbit integration method (Runge–Kutta, leapfrog, ...)</td><td colspan="3">adaptive-timestep Runge–Kutta, independently for each particle</td><td colspan="3">leapfrog or Hermite, shared for all particles</td></tr>
</table>

expensive

1. Statement of need

There are $\gtrsim$ 100 known stellar streams from tidally disrupting star clusters and satellite galaxies in the Milky Way alone [Mateu 23; Bonaca & Price-Whelan 25]. Their study reveals the assembly history and constrains the gravitational potential of the Galaxy;
moreover, dynamically cold / thin streams are very sensitive probes of dark matter at small scales.
Methods for simulating satellite disruption and stream formation differ in complexity and realism.

2. Test-particle simulations

- ◇ particles are seeded around Lagrange points
- + very fast, produce reasonably looking streams
- — no account for internal dynamics of the satellite
- — mass loss rate set manually (usually constant)
- — only stream particles are considered

3. Conventional *N*-body simulations

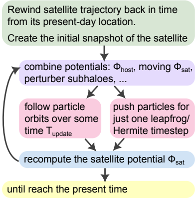
- + most realistic method: correct internal dynamics, mass loss rate, and stream morphology
- — but also most expensive
- — unless the host galaxy is a live system, adding dynamical friction is tricky
- — finding initial conditions that bring the satellite to the observed final position/velocity is tricky

4. Restricted *N*-body approach (for a lack of a better name)

- ◇ intermediate in realism and computational cost
- + satellite follows a prescribed trajectory (including dyn.friction) and arrives exactly where we want
- + realistic mass loss rate and stream density profile
- + internal dynamics followed reasonably well
- + two-body relaxation can be added explicitly using the Monte Carlo approach

5. Restricted *N*-body variants

difference in treatment of Φ_{sat}:
(a) prescribed manually;
(b) updated periodically;
(c) recomputed every timestep
(equivalent to SCF / EXP)



Rewind satellite trajectory back in time from its present-day location.
Create the initial snapshot of the satellite

combine potentials: Φ_{host}, moving Φ_{sat}, perturber subhaloes, ...

follow particle orbits over some time T_{update}

push particles for just one leapfrog/ Hermite timestep

recompute the satellite potential Φ_{sat}

until reach the present time