Few-body integrator with time-reversible adaptivity in Julia

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Purpose

- **Simulation**: long-time numerical integration of few-body gravitational problem involving close encounters:

$$\frac{dq_i}{dt} = v_i \qquad i = 1, \ldots, N$$
$$\frac{dv_i}{dt} = \sum_{j \neq i} \frac{Gm_j}{\|q_j - q_i\|^3}(q_j - q_i) \qquad i = 1, \ldots, N$$

- **Integrator**: based on IRKGL16 symmetric and symplectic Implicit Runge-Kutta method of order 16
- **Adaptive Step Size Control**:
  - Standard: qualitatively correct long-time behaviour is lost
  - Time-reversible Step Size: we expect the numerical solution to have long-time behaviour similar to that of the exact solution

Time-reversible adaptivity

- Consider the initial value problem of systems of ordinary differential equations of the form

$$\frac{du}{dt} = f(u), \quad u_0 = u(t_0)$$

where approximations are denoted as $u_n \approx u(t_n)$.

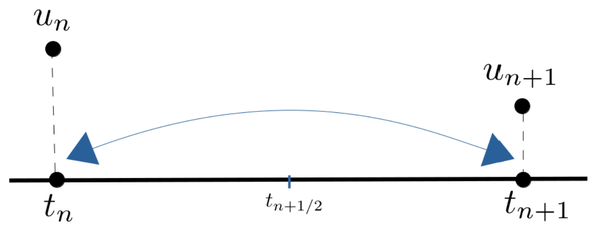


Figure 1. **Forward** and **backward integration**: same step size

Approach

- **Scheme of time-reversible adaptive-step based on IRKGL16**: the aproximations $u_n \approx u(t_n)$ are computed as

$$u_{n+1} = u_n + h_n \sum_{i=1}^{s} b_i f(U_{n,i})$$

where the stage vectors $U_{n,i}$ and h_n are implicitly defined at each step by

$$U_{n,i} = u_n + h_n \sum_{j=1}^{s} a_{ij} f(U_{n,j})$$
$$h_n = \Delta\tau\ \sigma(u_n).$$

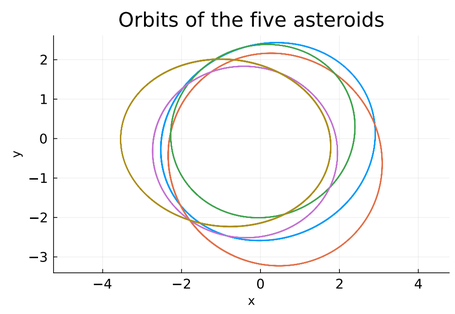
  - $\Delta\tau$=user supplied constant to specify the tolerance
  - $\boldsymbol{\sigma(u)}$= step-size function for the n-body problem:

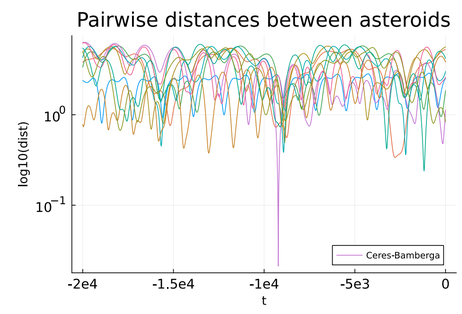
$$\sigma^{-1}(u_n) = \sum_{i=1}^{s} b_i K(U_{n,i}) \approx K(u(t_{n+1/2}))$$

where $K(u)$ is a time renormalization function for the n-body problem derived from the lower bound of the radius of convergence of the solution (see [3, p.179])

Test problem

- 15-body model of the Solar System
  - The Sun, all eight planets of the Solar System, Pluto and the five main bodies of the asteroid belt
  - Close encounters between some of the asteroids

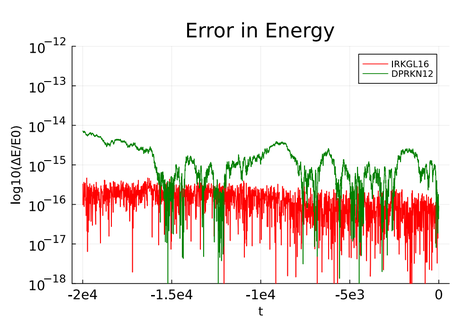


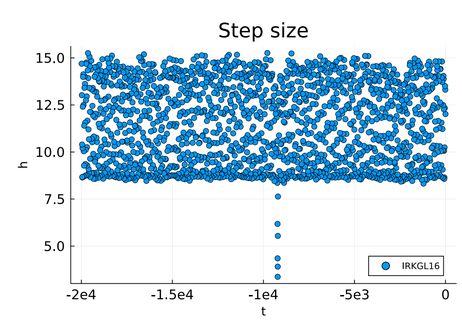


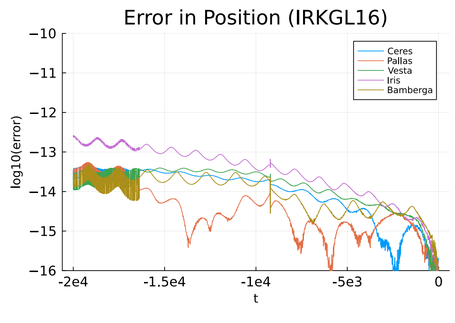
Results

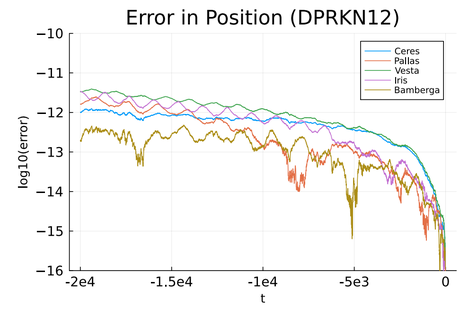
- Numerical integrations

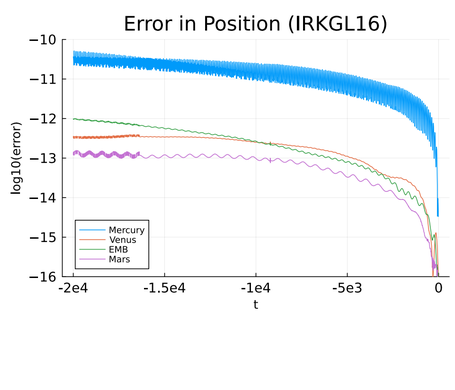
method	Dtau/tol	@btime	steps
IRKGL16	1.8	223ms	1,735
IRKGL16 (simd)	1.8	48ms	1,735
DPRKN12	1e-14	45ms	5,250

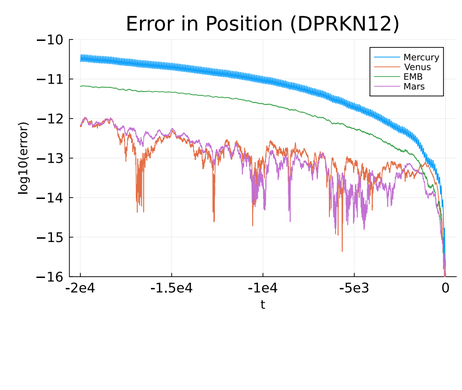












Our contribution

- Integrator for few-body problems that incorporate a time-reversible adaptivity mechanism
- and outperform state-of-the-art high order explicit Runge-Kutta schemes thanks to SIMD-vectorization.

References

[1] E.Hairer and D. Stoffer.
Reversible long-term integration with variable stepsizes.
SIAM Journal on Scientific Computing, 1997.

[2] J. Makazaga M. Antoñana, P. Chartier and A. Murua.
Global time-renormalization of the gravitational n-body problem.
SIAM Journal on Applied Dynamical System, 2020.

[3] J. Makazaga M. Antoñana, P. Chartier and A. Murua.
Majorant series for the n-body problem.
International Journal of Computer Mathematics, 2022.

Julia package

- https://github.com/mikelehu/NbodyIRKGL16.jl