Time-Series Analysis of EMRI Black Hole Simulations

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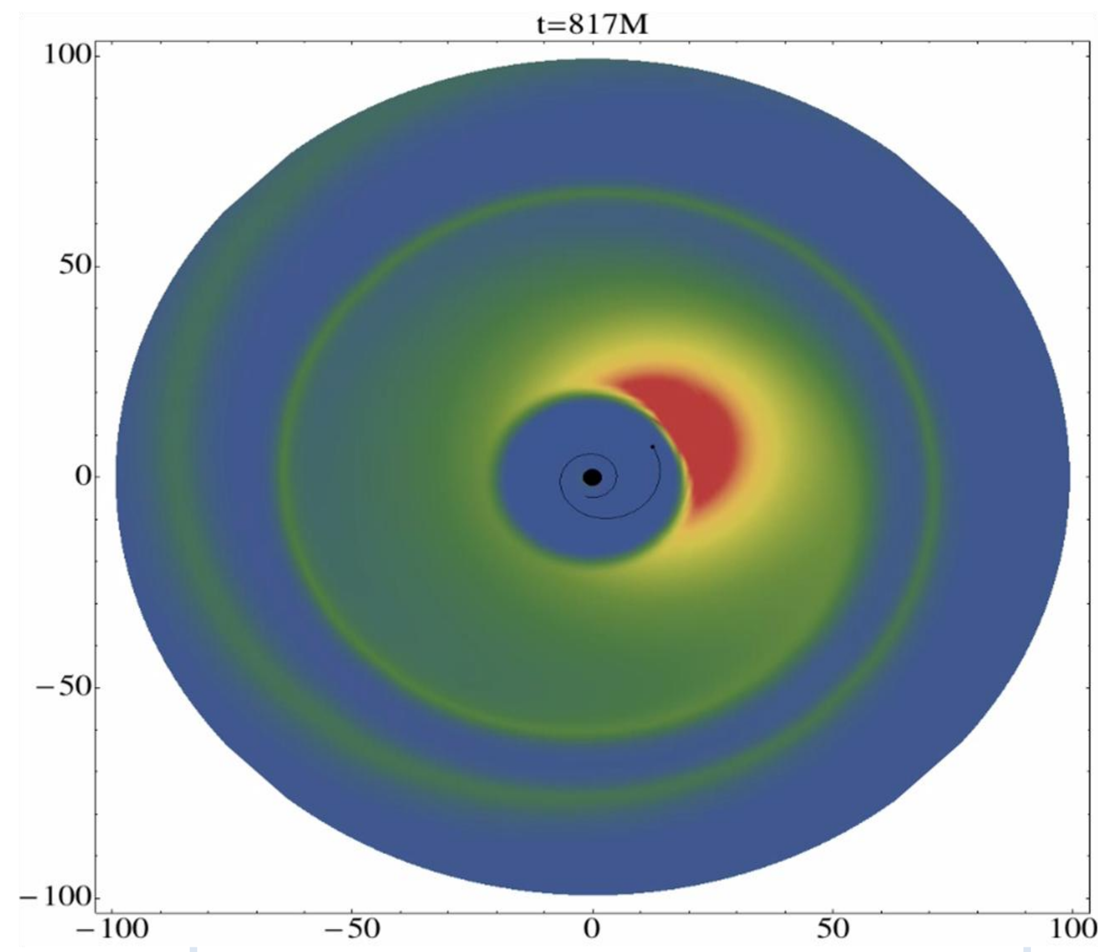
Introduction

EMRI (Extreme Mass Ratio Inspiral) black hole simulations describe the orbit of a small black hole around a much larger SMBH (supermassive black hole). These conditions are similar to those at the center of our galaxy.



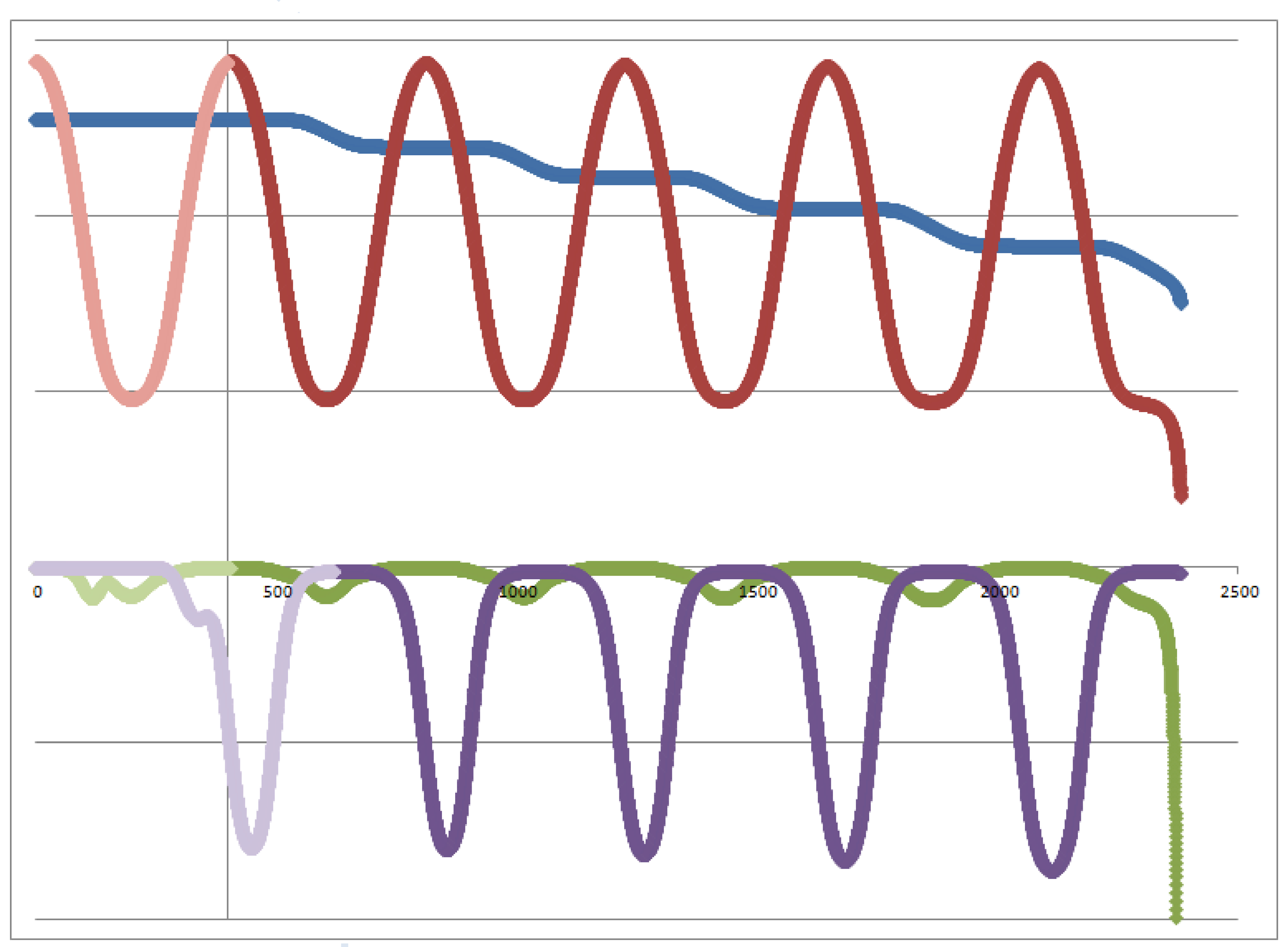
Snapshot of visualization of scalar charge of magnitude q = 1/32 with eccentricity e = 0.5. The red color shows a stronger intensity scalar field against the blue backdrop of a weaker one. The central black circle shows the location of the SMBH and the smaller dot shows the current location of the scalar charge. The line shows the last half orbit.

Models

Requires supercomputer calculations due to mass ratio of approximately 10^{-5}
Calculates orbital energy, angular momentum
Our Study: Scalar
•Charged particle in an orbit
•Simpler, tests numerical techniques
In the Future: EMRI
•More astrophysically accurate
•Complex

Scaled Time-Series

Simulation constantly generates data; useless until self-force varies periodically. Faint lines show data before valid waveforms propagate.



Energy flux (green and purple) is always negative. Total energy flux should equal energy lost for an orbit.

Legend:
Red .... Position
Blue .... Orbital Energy
Green .... Horizon Energy Flux
Purple .... Scri$^+$ Energy Flux

What is an orbit?
From one extrema to the next for each time-series. Problems arise when comparing orbital energy (at a single point) to energy flux (over an entire surface).

This Simulation

Describes orbiting scalar charge
Boundaries
•Horizon – surface of the supermassive black hole
•Scri$^+$ – aka null-infinity. Location of waves moving at the speed of light after an infinite amount of time

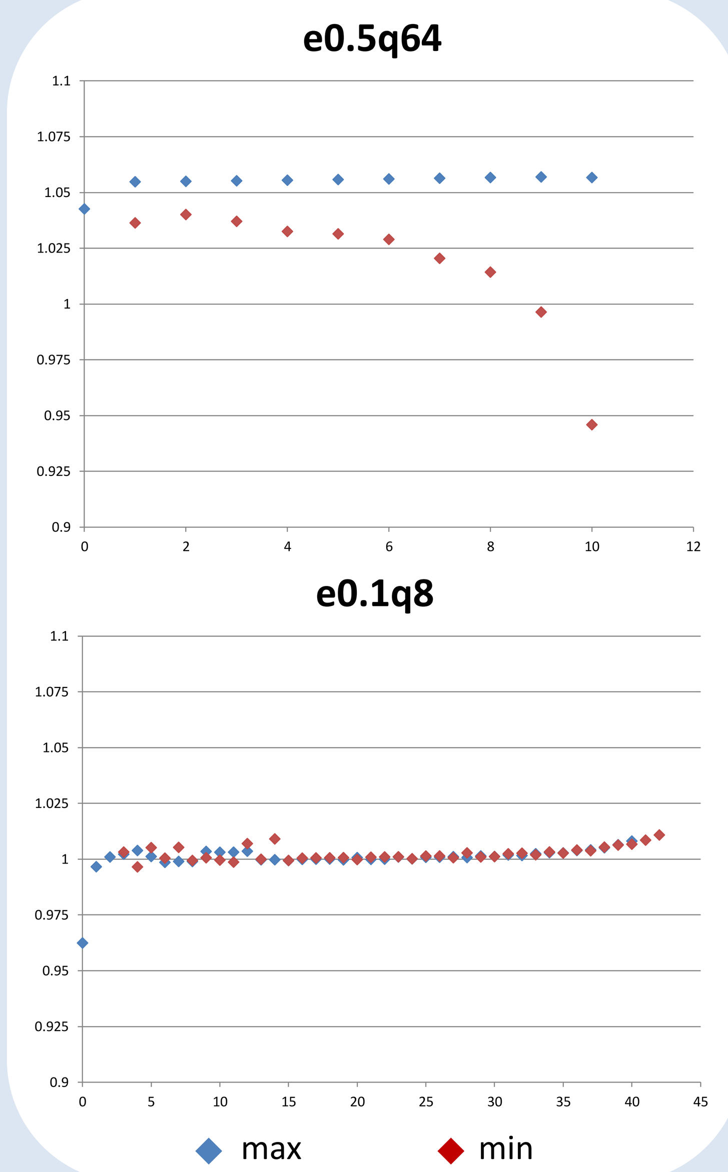
Objects in orbit have acceleration;
Acceleration produces waves, scalar or gravitational depending on the model;
Energy thus emitted is lost from the orbit

Program and Results

Program Design

Find change in Orbital Energy
•First find duration of orbit (based on position)
Find integrated Energy Flux
•First find duration of orbit (based on energy flux)
•Since values are discrete, not continuous, integrate using numerical integration
Compare Energy Flux Ratios
•Should be approximately one
•Deviations can be an indicator of how quickly an orbit evolves

Analysis tool developed here is valid for both Scalar and EMRI models.



Sample Simulations:
Follow the energy loss ratio for each orbit in a simulation. Shown are the e0.5q64 run with 13 orbits and the e0.1q8 run with 43 orbits.

An orbit evolves quickly when it loses large amounts of orbital energy and angular momentum.

These plots illustrate the differences in orbit evolution caused by the unique combination of charge and eccentricity. Quicker evolving orbits (more asymmetric) lead to the ratio deviating more from one at later times.

Ratios for all Simulations

e	q	max ratio ± error	min ratio ± error
0.5	1/32	1.0501 ± 0.0081%	0.9394 ± 0.3344%
0.5	1/64	1.0547 ± 0.0116%	0.9885 ± 0.4335%
0.1	1/8	1.0008 ± 0.0399%	0.9939 ± 0.5251%

Energy loss ratios for the three completed simulations show roughly all energy is propagated when expected.
Deviations from one results from reflections of the space-time curvature, variations in propagation times of the waves from the particle to different parts of the boundary.

Conclusion

Energy ratios are approximately one for all runs. This confirms the physics of the simulation.
My code accomplishes desired analysis of the time-series data, with applicability to more advanced future simulation's data.

Future Work

Simulation can include:
•Rotating Black Hole
•Calculated Angular Momentum
Program can include:
•Angular Momentum Analysis
•More accurate Location of Extrema

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