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.

Models

Requires supercomputer calculations due to mass ratio of approximately $10^6$
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

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

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).

Scaled Time-Series

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.

Ratios for all Simulations

<table>
<thead>
<tr>
<th>e</th>
<th>q</th>
<th>max ratio ± error</th>
<th>min ratio ± error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1/32</td>
<td>1.0501 ± 0.0081%</td>
<td>0.9394 ± 0.3344%</td>
</tr>
<tr>
<td>0.5</td>
<td>1/64</td>
<td>1.0547 ± 0.0116%</td>
<td>0.9885 ± 0.4335%</td>
</tr>
<tr>
<td>0.1</td>
<td>1/8</td>
<td>1.0008 ± 0.0399%</td>
<td>0.9939 ± 0.5251%</td>
</tr>
</tbody>
</table>

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.

Conclusion

Energy loss 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.

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

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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