Collisions of Primordial Black Holes and Neutron Stars

Introduction

Flat Star Model

Numerical Approach

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Introduction

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Flat Star

Numerica Approach A primordial black hole is a black hole that was hypothetically created in the early universe.

Flat Star Model

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Flat Star Model

Solving for φ Solving for η Plotting η Solving for E

Numeric Approacl

- Neutron stars are flat and infinite
- Primordial black holes are point masses
- Neutron stars are incompressible fluids
- Gravitational interactions are Newtonian
- Constant velocity

Eigenfunctions of Laplacian

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Numerical Approach Assume a product solution for the velocity potential and solve the Laplacian.

$$\varphi = R(r)Z(z)\Theta(\theta)T(t)$$

$$\nabla^{2}\varphi = 0$$

$$\implies \varphi \propto \begin{cases} J_{\mu}(kr) \\ Y_{\mu}(kr) \end{cases} \begin{cases} e^{-kz} \\ e^{kz} \end{cases} \begin{cases} \sin(\mu\theta) \\ \cos(\mu\theta) \end{cases} T(t)$$

$$\implies \varphi \propto J_{0}(kr)e^{kz}T(t)$$

T(t) comes from boundary conditions.

Solving for φ

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$$\begin{split} \Phi &= \frac{-Gm}{\sqrt{r^2 + (z + vt)^2}} \\ & \left(\frac{\partial^2 \varphi}{\partial t^2} + g \frac{\partial \varphi}{\partial z}\right) \bigg|_{z=0} = -\frac{\partial \Phi}{\partial t}\bigg|_{z=0} \\ \varphi &= \frac{Gmv}{g} \int_0^\infty \frac{J_0(kr)e^{kz}}{1 + kv^2/g} \left(-\operatorname{sgn}(t)e^{-kv|t|} + 2H(t) \operatorname{cos}(\omega_k t)\right) dk \\ & \qquad \qquad \text{with } \omega_k^2 = gk \end{split}$$

Deformation of Surface

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$$\begin{split} \left. \frac{\partial \varphi}{\partial z} \right|_{z=0} &= \frac{\partial \eta}{\partial t} \\ \eta &= \frac{Gm}{g} \int_0^\infty \frac{J_0(kr)}{1 + kv^2/g} \left(e^{-kv|t|} + 2H(t)v \sqrt{\frac{k}{g}} \sin(\omega_k t) \right) dk \end{split}$$

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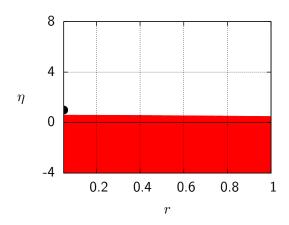


Figure : t = -1 s.

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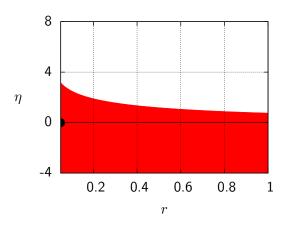


Figure : t = 0 s.

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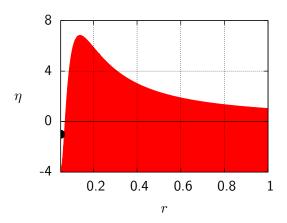


Figure : t = 1 s.

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Solving for E

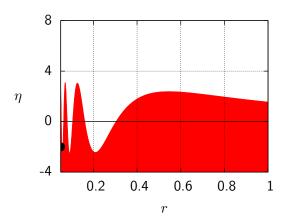


Figure : t=2 s.

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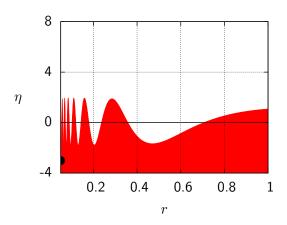


Figure : t = 3 s.

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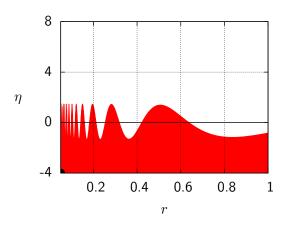


Figure : t=4 s.

Energy Transferred

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$$\begin{split} E &= \lim_{t \to \infty} \frac{1}{2} \rho \int_{-\infty}^{0} \int_{0}^{\infty} |\nabla \varphi|^{2} \, r dr dz \int_{0}^{2\pi} d\theta \\ &+ \rho g \int_{0}^{\infty} \int_{0}^{\eta} z dz \, r dr \int_{0}^{2\pi} d\theta \\ &= 4\pi \rho \frac{G^{2} m^{2}}{g} \end{split}$$

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Numerical

Approach Smooth Particle Hydrodynamics