Spherical solutions for stars

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Rochester Institute of Technology

General Relativity I Presentations
December 14th, 2015

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Introduction

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Spherically symmetric coordinates

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Two-sphere in flat spacetime

General metric

$$ds^2 = -\mathrm{d}t^2 + \mathrm{d}r^2 + r^2(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2)$$

Metric on 2-sphere

$$\mathrm{d}l^2 = r^2(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2) \equiv r^2\mathrm{d}\Omega^2$$

Schutz (2009, p. 256)

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Two-sphere in curved spacetime

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$$\mathrm{d}l^2 = f(r', t)\mathrm{d}\Omega^2$$

Relation to r

$$f(r', t) \equiv r^2$$

Schutz (2009, pp. 256–257)

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└─Two-sphere in curved spacetime

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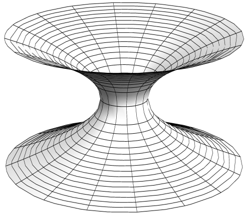
Meaning of r



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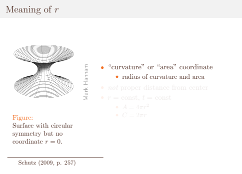
- “curvature” or “area” coordinate
  - radius of curvature and area
- *not* proper distance from center
- $r = \text{const}$, $t = \text{const}$
  - $A = 4\pi r^2$
  - $C = 2\pi r$

Figure:
Surface with circular symmetry but no coordinate $r = 0$.

Schutz (2009, p. 257)



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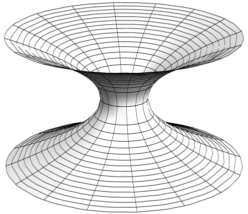

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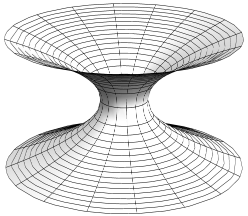

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g_{00}, g_{0r}, and g_{rr} functions of t and r

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Static spacetimes

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Motivation

- leads to simple derivation of Schwarzschild metric
- generalizes to spherically symmetric, asymptotically flat Einstein vacuum field equations
- Birkhoff's theorem

Schutz (2009, p. 263) and Misner, Thorne, and Wheeler (1973, p. 843)

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Definition

A spacetime is static if we can find a time coordinate t for which

(i) the metric independent of t

$$g_{\alpha\beta,t} = 0$$

(ii) the geometry unchanged by time reversal

$$t \to -t$$

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  - e.g. rotating star

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Time reversal

$$\mathbf{\Lambda} : (t, x, y, z) \to (-t, x, y, z)$$

$$g_{\bar\alpha\bar\beta} = \Lambda^{\alpha}{}_{\bar\alpha}\Lambda^{\beta}{}_{\bar\beta} g_{\alpha\beta} = g_{\alpha\beta}$$

Transformation

$$\Lambda^{0}{}_{\bar0} = x^{0}{}_{,\bar0} = -x^{0}{}_{,0} = -1$$
$$\Lambda^{i}{}_{\bar j} = x^{i}{}_{,\bar j} = x^{i}{}_{,j} = \delta^{i}{}_{j}$$
$$\Lambda^{0}{}_{\bar i} = x^{0}{}_{,\bar i} = x^{0}{}_{,i} = 0$$

Metric

$$g_{\bar0\bar0} = (\Lambda^{0}{}_{\bar0})^2 g_{00} = g_{00}$$
$$g_{\bar0\bar r} = \Lambda^{0}{}_{\bar0}\Lambda^{r}{}_{\bar r} g_{0r} = -g_{0r}$$
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The metric

Simplified metric

$$\mathrm{d}s^2 = g_{00}\,\mathrm{d}t^2 + g_{rr}\,\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$$

Replacement

$$g_{00} \to -e^{2\Phi}, \quad g_{rr} \to e^{2\Lambda}, \quad \text{provided } g_{00} < 0 < g_{rr}$$

Static spherically symmetric metric

$$\mathrm{d}s^2 = -e^{2\Phi}\,\mathrm{d}t^2 + e^{2\Lambda}\,\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$$

$$\lim_{r\to\infty}\Phi(r) = \lim_{r\to\infty}\Lambda(r) = 0$$

Schutz (2009, pp. 258–259)

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- limits at infinity tell us that spacetime is *asymptotically flat*

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Einstein Tensor

General Einstein tensor

$$G_{\alpha\beta} = R^{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R$$

Einstein tensor components

$$G_{tt} = \frac{1}{r^2} e^{2\Phi} \frac{\mathrm{d}}{\mathrm{d}r} [r(1 - e^{-2\Lambda})],$$

$$G_{rr} = -\frac{1}{r^2} e^{2\Lambda} (1 - e^{-2\Lambda}) + \frac{2}{r} \Phi'$$

$$G_{\theta\theta} = r^2 e^{-2\Lambda} [\Phi'' + (\Phi')^2 + \Phi'/r - \Phi'\Lambda' - \Lambda'/r],$$

$$G_{\phi\phi} = \sin^2\theta G_{\theta\theta}$$

Schutz (2009, pp. 165, 260)

- $x' \equiv \mathrm{d}x/\mathrm{d}r$

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Static perfect fluid

Static perfect fluid

Four-velocity

Constraints

$$U^i = 0 \text{ (static)} \qquad \vec{U} \cdot \vec{U} = -1 \text{ (conservation law)}$$

Solving for U^0

$$g_{00} (U^0)^2 = -1 \implies U^0 = (-g_{00})^{-1/2} = e^{-\Phi}$$

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- "conservation law" is the conservation of four-momentum

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Stress–energy tensor

$T_{\alpha\beta}$ for perfect fluid

$$T_{\alpha\beta} = (\rho + p)U_\alpha U_\beta + p g_{\alpha\beta}$$

Components of $T_{\alpha\beta}$

$$T_{00} = (\rho + p)e^{2\Phi} + p(-e^{2\Phi}) = \rho e^{2\Phi}$$

$$T_{\alpha\beta} = 0 \text{ for } \alpha \neq \beta; \quad T_{ii} = p g_{ii}$$

$$T_{rr} = p e^{2\Lambda}; \quad T_{\theta\theta} = p r^2; \quad T_{\phi\phi} = p r^2 \sin^2\theta = T_{\theta\theta}\sin^2\theta$$

Schutz (2009, p. 260)

- $T_{\alpha\beta} = 0$ because
  - the cross terms make $g_{\alpha\beta} = 0$
  - T_{0i} makes one of the U's $U_i = 0$
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Equation of state

Local thermodynamic equilibrium

$$p = p(\rho, S) \approx p(\rho)$$

- pressure related to energy density and specific entropy
- we often deal with negligibly small entropies

Schutz (2009, p. 261)

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Equations of motion

Conservation laws

$$T^{\alpha\beta}{}_{;\beta} = 0$$

- symmetries make only non-trivial solution $\alpha = r$
  TODO: prove

Equation of motion

$$(\rho + p)\frac{\mathrm{d}\Phi}{\mathrm{d}r} = -\frac{\mathrm{d}p}{\mathrm{d}r}$$

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Mass function

Einstein field equations

$$G_{00} = 8\pi T_{00} \implies \frac{1}{r^2} e^{2\Phi} \frac{\mathrm{d}}{\mathrm{d}r}[r(1 - e^{-2\Lambda})] = 8\pi\rho e^{2\Phi}$$

$m(r)$

$$m(r) \equiv \frac{1}{2} r(1 - e^{-2\Lambda}) \quad \text{or} \quad g_{rr} = e^{2\Lambda} \equiv \left(1 - \frac{2m(r)}{r}\right)^{-1}$$

Relation to energy density

$$\frac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi r^2 \rho$$

Schutz (2009, pp. 260–262)

- inspect $(0, 0)$ component of Einstein equations
- in Newtonian limit, $m(r)$ is mass within radius r

$$m(r) = 4\pi \int_0^r (r')^2 \rho(r') \, \mathrm{d}r'$$

- doesn't work in GR, because total energy is not localizable

Mass function

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Exterior Geometry

Exterior Geometry

Schwarzschild metric I

Condition

$$\rho = p = 0$$

Consequences

$$\frac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi r^2 \rho = 0 \qquad m(r) = M$$

$$\frac{\mathrm{d}\Phi(r)}{\mathrm{d}r} = \frac{m(r) + 4\pi r^3 p}{r[r - 2m(r)]} = \frac{M}{r(r - 2M)} \qquad \Phi(r) = \frac{1}{2}\log\left(1 - \frac{2M}{r}\right)$$

Schutz (2009, pp. 262–263)

- the external conditions just state we are in a vaccuum
- breaks down when matter surrounds star
- M is a constant

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Schwarzschild metric II

First two metric components

$$g_{tt} = -e^{2\Phi} = -\left(1 - \frac{2M}{r}\right) \qquad g_{rr} = e^{2\Lambda} = \left(1 - \frac{2M}{r}\right)^{-1}$$

Schwarzschild metric

$$\mathrm{d}s^2 = -\left(1 - \frac{2M}{r}\right)\mathrm{d}t^2 + \left(1 - \frac{2M}{r}\right)^{-1}\mathrm{d}r^2 + r^2\,\mathrm{d}\Omega^2$$

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Far-field metric

Condition

$$r \gg M$$

Far-field Schwarzschild metric

$$\mathrm{d}s^2 \approx -\left(1 - \frac{2M}{r}\right)\mathrm{d}t^2 + \left(1 + \frac{2M}{r}\right)\mathrm{d}r^2 + r^2\,\mathrm{d}\Omega^2$$

Far-field Schwarzschild metric (Cartesian)

$$\mathrm{d}s^2 \approx -\left(1 - \frac{2M}{R}\right)\mathrm{d}t^2 + \left(1 + \frac{2M}{R}\right)(\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2)$$

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- far-field metric of a star
  - mass M
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Birkhoff's Theorem

Let the geometry of a given region of spacetime:

1. be spherically symmetric
2. be a solution to the Einstein field equations in vacuum.

Then that geometry is necessarily a piece of the Schwarzschild geometry.

(Proof given in Misner, Thorne, and Wheeler (1973, pp. 843–844))

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Interior structure

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Tolman–Oppenheimer–Volkov (T–O–V) equation

Condition

$$\rho \neq 0; \quad p \neq 0$$

Recall

$$(\rho + p)\frac{\mathrm{d}\Phi}{\mathrm{d}r} = -\frac{\mathrm{d}p}{\mathrm{d}r} \qquad \frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{m(r) + 4\pi r^3 p}{r[r - 2m(r)]}$$

T–O–V equation

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- T–O–V equation coupled with $\mathrm{d}m/\mathrm{d}r$ and $p(\rho)$
  - 3 equations
  - 3 unknowns (m, ρ, p)
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Newtonian hydrostatic equilibrium

Newtonian limit

$$p \ll \rho; \quad 4\pi r^3 p \ll m; \quad m \ll r$$

Equation of hydrostatic equilibrium

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{\rho m(r)}{r^2}$$

Schutz (2009, pp. 265–266) and Hansen and Kawaler (1994, p. 3)

- Newtonian limit reduces the T–O–V equation to HSE

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