A survey of gravitational waves, the Bondi-Sachs formalism and the gravitational memory effect in general relativity and beyond

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Bondi-Sachs formalism in a nutshell

Description at null-infinity of the dynamic and, in particular, the change of mass and total momentum of a system through the emission of gravitational waves.

Objectives

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- Explain what the news function / tensor is
- Show where the mass-loss and momentum-loss formulae come from
- Explain briefly what the memory effect is and its relation to the news tensor

Preliminaries

Notation

- Signature: $(-,+,+,+)$
- Partial derivatives: f_u, f_r, f_θ, f_ϕ, $\dots$, or ∂_μ for tensors
- General tensor identities: g_{ab}, R_{ab}, $\dots$
- Tensor identities in a given base: $g_{\mu\nu}$, $R_{\mu\nu}$, $\dots$
- "Geometrized" units $G = c = 1$

A link to all sources, a copy of the thesis and these slides is provided at the end of this presentation.

Retarded time

Consider the Minkowski metric:

$$g = -\mathrm{d}t^2 + \mathrm{d}r^2 + r^2(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2). \tag{1}$$

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Thus, equation (1) becomes

$$g = -\mathrm{d}u^2 - 2\mathrm{d}u\,\mathrm{d}r + r^2(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2) \qquad (2)$$

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The coordinate u satisfies:

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Hypersurfaces $u = \mathrm{constant}$ are light-like. Normal vector k^a of such surfaces satisfies

$$k_\mu = \partial_\mu u, \qquad k^a k_a = 0, \qquad k^b \nabla_b k^a = 0,$$

and generate rays, along which θ and ϕ are constant.

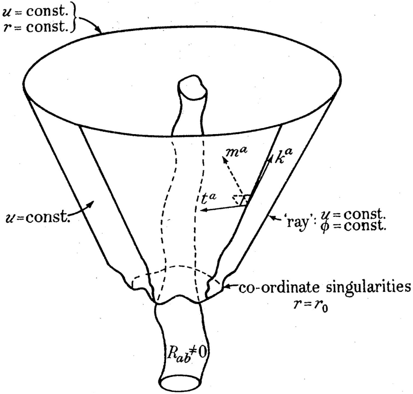

Figure: Illustration of a retarded time coordinate system. Source [5]

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- Axially symmetric (requirement is dropped later on)

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- θ and ϕ constant along rays

The Bondi metric

Thus, we arrive at the metric first presented by Bondi in [1]:

$$
\begin{aligned}
g = (U^2 r^2 \mathrm{e}^{2\gamma} - V r^{-1} \mathrm{e}^{2\beta}) \mathrm{d}u^2 &- 2\mathrm{e}^{2\beta} \mathrm{d}u \, \mathrm{d}r \\
&- 2Ur^2 \mathrm{e}^{2\gamma} \mathrm{d}u \, \mathrm{d}\theta + r^2 (\mathrm{e}^{2\gamma} \mathrm{d}\theta^2 + \mathrm{e}^{-2\gamma} \sin^2\theta \, \mathrm{d}\phi^2),
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together with its inverse

$$g^{\mu\nu} = \begin{pmatrix} 0 & -\mathrm{e}^{-2\beta} & 0 & 0 \\ -\mathrm{e}^{-2\beta} & V\mathrm{e}^{-2\beta} r^{-1} & -U\mathrm{e}^{-2\beta} & 0 \\ 0 & -U\mathrm{e}^{-2\beta} & \mathrm{e}^{-2\gamma} r^{-2} & 0 \\ 0 & 0 & 0 & \mathrm{e}^{2\gamma} r^{-2} \sin^{-2}\theta \end{pmatrix},$$

where β, γ, U and V are functions of u,r and θ.

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where β, γ, U and V are functions of u,r and θ.
Note that $g^{00} = 0$, hence $g^{\mu\nu}(\partial_\mu u)(\partial_\nu u) = 0$.

The Bondi metric

For the Bondi metric

$$g = (U^2 r^2 \mathrm{e}^{2\gamma} - V r^{-1} \mathrm{e}^{2\beta}) \mathrm{d}u^2 - 2\mathrm{e}^{2\beta} \mathrm{d}u \, \mathrm{d}r \\ - 2Ur^2 \mathrm{e}^{2\gamma} \mathrm{d}u \, \mathrm{d}\theta + r^2 (\mathrm{e}^{2\gamma} \mathrm{d}\theta^2 + \mathrm{e}^{-2\gamma} \sin^2\theta \, \mathrm{d}\phi^2),$$

choosing the following values for the coefficients

$$\beta = 0, \qquad \gamma = 0, \qquad U = 0, \qquad V = r,$$

yields the Minkowski metric.

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Furthermore, from the Bianchi identities it follows that

$$R_{01} = 0$$

as a consequence of

$$R_{11} = R_{12} = R_{22} = R_{33} = 0 \tag{4}$$

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known as *main equations*, and the supplementary conditions

$$0 = r^{-2}\mathrm{e}^{-2\beta}(r^2 R_{02})_r, \tag{5}$$

$$0 = r^{-2}\mathrm{e}^{-2\beta}(r^2 R_{00})_r + (g^{12}\partial_1 + g^{22}\partial_2 - g^{\mu\nu}\Gamma^2{}_{\mu\nu})R_{02}, \tag{6}$$

derived from the Bianchi identities similar to $R_{01} = 0$.

Series expansion

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Series expansion

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$$\left.\begin{aligned} \gamma &= \gamma_1 r^{-1} + \gamma_2 r^{-2} \dots \\ \beta &= \dots \beta_{-1} r + \beta_0 + \beta_1 r^{-1} + \beta_2 r^{-2} \dots \\ U &= \dots U_{-1} r + U_0 + U_1 r^{-1} + U_2 r^{-2} \dots \\ V &= \dots V_{-1} r + V_0 + V_1 r^{-1} + V_2 r^{-2} \dots \end{aligned}\right\} . \tag{7}$$

Equivalent to

$$\lim_{r \to \infty} (r\gamma)_r |_{u=\mathrm{const}} = 0 \tag{8}$$

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$$\gamma = cr^{-1} + [C - \frac{1}{6}c^3]r^{-3} + \ldots,$$
$$\beta = -\frac{1}{4}c^2 r^{-2} + \ldots,$$
$$U = -(c_\theta + 2c\cot\theta)r^{-2} + [2N + 3cc_\theta + 4c^2\cot\theta]r^{-3} + \ldots,$$
$$V = r - 2M - [N_\theta + N\cot\theta - c_\theta^2 - 4cc_\theta - \frac{1}{2}c^2(1 + 8\cot^2\theta)]r^{-1} + \ldots,$$

where $c(u,\theta)$, $M(u,\theta)$ and $N(u,\theta)$ are integration functions from solving the vacuum field equations. $C(u,\theta)$ is a composition of them.

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yield

$$M_u = -c_u^2 + \frac{1}{2}(c_{\theta\theta} + 3c_\theta \cot\theta - 2c)_u, \qquad (9)$$
$$-3N_u = M_\theta + 3cc_{u\theta} + 4cc_u \cot\theta + c_u c_\theta. \qquad (10)$$

Known as the mass-loss and momentum-loss formulae.

News and mass-loss

The mass of the system is defined as the mean value of $M(u, \theta)$ over the sphere

$$m(u) = \frac{1}{2} \int_0^{\pi} M(u, \theta) \sin\theta \, \mathrm{d}\theta \,. \tag{11}$$

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Hence

$$m_u = -\frac{1}{2} \int_0^\pi c_u^2 \sin\theta \, \mathrm{d}\theta \,. \tag{12}$$

Therefore, changes in the system are contained within c_u, which receives for this reason the name *news function*.

Main result of the publication of Bondi, Van der Burg and Metzner

The mass of a system is constant if and only if there is no news. If there is news, the mass decreases monotonically as long as the news continues [2].

The Bondi-Sachs metric

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We now turn our attention to the more general Bondi-Sachs metric. We list again our requirements for the metric:

- Describe an isolated system
- Asymptotically flat
- Not necessarily static
- ~~Axially symmetric~~

The Bondi-Sachs metric

As for the coordinates u, r, θ and ϕ, we wish to keep the properties of the coordinates of the retarded time Minkowski metric:

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- r is the corresponding luminosity distance, i.e. area of surface element $u, r = constant$ is $r^2 \sin\theta \, \mathrm{d}\theta \, \mathrm{d}r$
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with the inverse

$$g^{-1} = 2F\mathrm{e}^{-2\beta}\partial_r\partial_r - 2\mathrm{e}^{2\beta}\partial_u\partial_r - 2\mathrm{e}^{-2\beta}U^A\partial_r\partial_A + r^{-2}q^{AB}\partial_A\partial_B, \tag{14}$$

where $A, B = 2, 3$ and $\sigma^{2,3} = \theta, \phi$.

Comparison with the Bondi metric

The Bondi metric

$$g = (U^2 r^2 \mathrm{e}^{2\gamma} - V r^{-1} \mathrm{e}^{2\beta}) \mathrm{d}u^2 - 2\mathrm{e}^{2\beta} \mathrm{d}u \, \mathrm{d}r \\ - 2 U r^2 \mathrm{e}^{2\gamma} \mathrm{d}u \, \mathrm{d}\theta + r^2 (\mathrm{e}^{2\gamma} \mathrm{d}\theta^2 + \mathrm{e}^{-2\gamma} \sin^2 \theta \, \mathrm{d}\phi^2),$$

is a special case of the Bondi-Sachs metric

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To see this, let

$$F = V/2r, \qquad \beta = \beta_{\mathrm{Bondi}}, \qquad U^A = (U_{\mathrm{Bondi}}, 0),$$

$$q_{AB} = \begin{pmatrix} \mathrm{e}^{2\gamma} & 0 \\ 0 & \mathrm{e}^{-2\gamma} \sin^2\theta \end{pmatrix}$$

Series expansion

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\begin{aligned}
F(u,r,\sigma^A) &= \bar{F}(u,\sigma^A) - \frac{M}{r} + \ldots, \\
\beta(u,r,\sigma^A) &= \frac{\bar{\beta}(u,\sigma_A)}{r^2} + \ldots, \\
q_{AB}(u,r,\sigma^A) &= \bar{q}_{AB}(u,\sigma^A) + \frac{c_{AB}}{r} + \ldots, \\
U^A(u,r,\sigma^A) &= \frac{\bar{U}(u,\sigma^A)}{r^2} - \frac{2}{3r^3}\bar{q}^{AB}\left(\bar{P}^A + c_{BC}\bar{U}^C + \partial_B\bar{\beta}\right) + \ldots,
\end{aligned}
$$

where $\bar{q}_{AB}$ is the metric of the round 2-sphere.

Equations of motion

Solving Einstein's field equations order by order in r yields

$$
\begin{aligned}
0 &= (\bar{q}_{AB})_u, \\
0 &= \bar{\beta} + \frac{1}{32} c_{AB} c^{AB}, \\
0 &= \bar{R} - 4\bar{F}, \\
0 &= \bar{U}^A + \frac{1}{2} \bar{\nabla}_B c^{AB},
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where $\bar{R}$ is the Ricci scalar and ∇_A is the Levi-Civita connection with respect to the $\bar{q}_{AB}$ metric.
We define the *news tensor* as follows:

$$
N_{AB} = (c_{AB})_u \tag{15}
$$

Equations of motion: Mass-loss and momentum-loss formulae

Using our definition of the news tensor while solving the field equations yields the loss formulae:

$$
\begin{aligned}
M_u &= -\frac{1}{8}N_{AB}N^{AB} + \frac{1}{4}\bar{\nabla}_A\bar{\nabla}_B N^{AB}, \\
(\bar{P}_A)_u &= \bar{\nabla}_A M + \frac{1}{8}\bar{\nabla}_A\left(c^{BC}N_{CB}\right) - \frac{1}{4}N^{BC}\bar{\nabla}_A c_{BC} \\
&\quad + \frac{1}{4}\bar{\nabla}_C\left(\bar{\nabla}_A\bar{\nabla}_B C^{BC} - \bar{\nabla}^C\bar{\nabla}^B C_{AB}\right) \\
&\quad + \frac{1}{4}\bar{\nabla}_B\left(N^{BC}c_{AC} - c^{BC}N_{AC}\right).
\end{aligned}
$$

Memory effect

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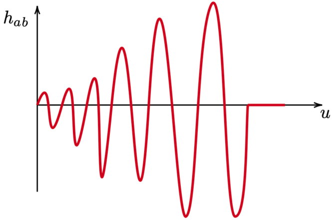
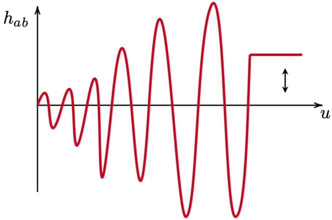
Permanent relative displacement due to a burst of gravitational waves [3].

Memory effect



(a) Without memory effect



(b) With memory effect

Figure: Sketch of the metric perturbation as a function of time. Source [3]

Memory effect

Let us consider the deviation equation for particles in free fall:

$$(v^a \nabla_a)^2 \xi^b = -R_{acd}{}^b v^a v^d \xi^c. \tag{16}$$

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$$(\xi^\mu)_{uu} = -R_{0\alpha 0}{}^\mu \xi^\alpha, \tag{17}$$

where for $r \to \infty$, $R_{abcd} \sim C_{abcd}$ (C_{abcd} is the Weyl tensor).

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Thus, the news tensor is not only related to the energy radiated through gravitational waves, but also the memory effect.

Further developments

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- Using a set of coordinates based on the retarded time Minkowski metric we introduced the family of Bondi-Sachs metrics.
- Solving Einstein's vacuum equations yields the loss formulae, which describe change of mass and total momentum of a system due to emission of gravitational waves.
- The news tensor, closely related to the loss formulae, describes how the emission of gravitational waves is related to the memory effect in general relativity.
- It may be possible in the future to discard or validate theories of alternative gravity based on these results.

Sources

[1] Hermann Bondi. *Gravitational Waves in General Relativity*.

[2] Hermann Bondi, M. G. J. Van der Burg, and A. W. K. Metzner. *Gravitational waves in general relativity, VII. Waves from axi-symmetric isolated system*.

[3] Luca Ciambelli et al. *Cornering Quantum Gravity*.

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[5] R. K. : Sachs and Hermann Bondi. *Gravitational waves in general relativity VIII. Waves in asymptotically flat space-time*.

Detailed list of sources and a copy of the thesis are available on `https://thomaslabs.org/talks/bachelor-thesis.html`