How the green light was given for gravitational wave search

Paweł Nurowski

Center for Theoretical Physics
Polish Academy of Sciences

Simons Center for Geometry and Physics
14 December 2016

Plan

Gravitational waves: Einstein and Rosen 1937 - plane waves are unphysical

ON GRAVITATIONAL WAVES.

BY

A. EINSTEIN and N. ROSEN.

ABSTRACT.

The rigorous solution for cylindrical gravitational waves is given. For the convenience of the reader the theory of gravitational waves and their production, already known in principle, is given in the first part of this paper. After encountering relationships which cast doubt on the existence of *rigorous* solutions for undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

Einstein A, Rosen N, *On gravitational waves*, Journ. of Franklin Institute, 223, (1937).

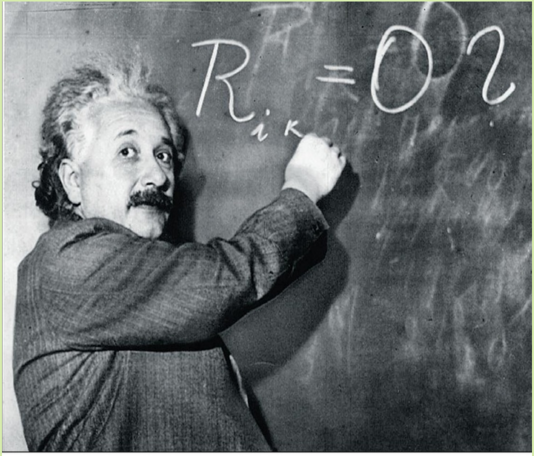
has the same sign. Progressive waves therefore produce a secular change in the metric.

This is related to the fact that the waves transport energy, which is bound up with a systematic change in time of a gravitating mass localized in the axis $x = 0$.

Note.—The second part of this paper was considerably altered by me after the departure of Mr. Rosen for Russia since we had originally interpreted our formula results erroneously. I wish to thank my colleague Professor Robertson for his friendly assistance in the clarification of the original error. I thank also Mr. Hoffmann for kind assistance in translation.

A. EINSTEIN.

People: Albert Einstein (14.3.1879-18.04.1955)



People: Nathan Rosen (22.3.1909-18.12.1995)

Historian: Daniel Kennefick

Einstein Versus the *Physical Review*

A great scientist can benefit from peer review, even while refusing to have anything to do with it.

Daniel Kennefick

Daniel Kennefick *is a visiting assistant professor of physics at the University of Arkansas at Fayetteville and an editor with the Einstein Papers Project at the California Institute of Technology.*

this matter.

On 30 July, Tate replied that he regretted Einstein's decision to withdraw the paper, but stated that he would

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$$g = e^{2\phi}(d\tau^2 - d\xi^2) - u^2\left(e^{2\beta}d\eta^2 + e^{-2\beta}d\zeta^2\right)$$

with $u = \tau - \xi$, and the unknowns $\beta = \beta(u)$, $\phi = \phi(u)$;

- then the Einstein equations $Ric(g) = 0$ imposed on the unknown functions β and ϕ reduced to: $\phi' = u\beta'^2$ and $u\beta'' + 2\beta' - u^2\beta'^3 = 0$.
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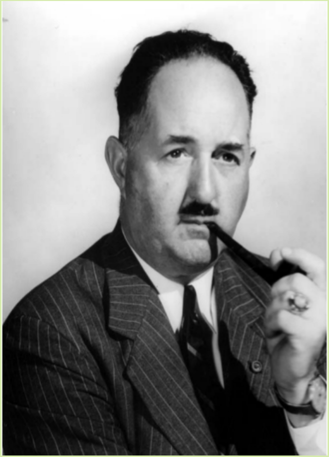

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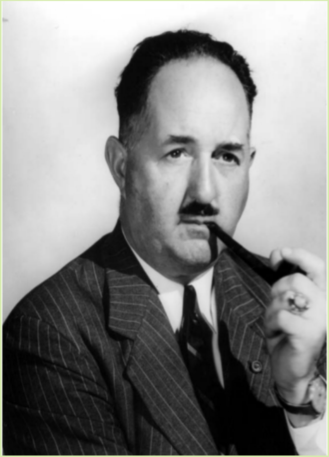

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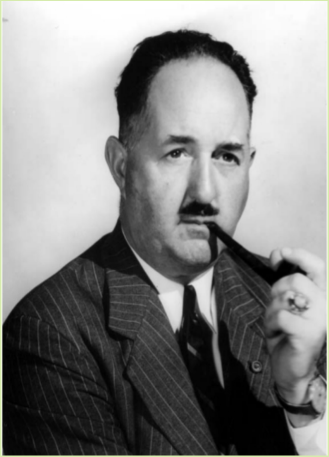

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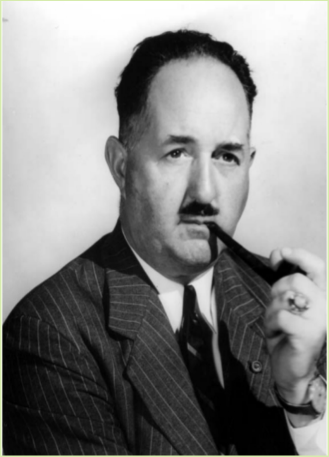

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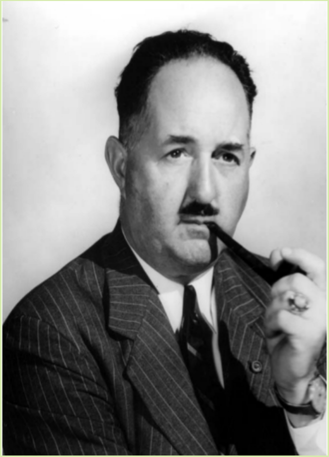

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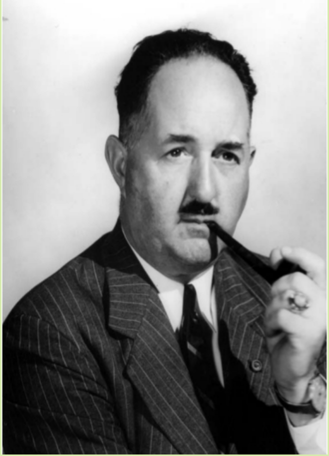

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Who was the referee?

Daniel Kennefick look at the logbook of *Phys. Rev.* from 1936:

1936

NAME	DATE IN	REFEREE	DATE IN	TO AUTHOR	TO N.Y.	ISSUE	RE-JECTED
Gregory	7/24	[illegible] 6/4	6/8				6/12
Einstein & Rosen	6/1	Robertson 7/6	7/17	7/23			
[illegible]	[illegible]				4/14	MAY 15, 1936	
[illegible]	3/28		4/6	4/9	4/17/36	JUNE [illegible]	

Gravitational waves: Einstein and Rosen 1937

- Both Rosen, but what is more important **Einstein**, acccepted that they have **a cylindrical wave**, but they lost the hope for a **plane wave** to be admitted by the full theory!
- Einstein truly belived that a plane wave should admit a **global coordinate system** in which it is expressed;
- THIS STOPPED THE SEARCH FOR GRAVITATIONAL WAVES FOR ABOUT 20 YEARS!
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Gloom and doom period: 1937-1956

RED LIGHTS!

Do the fully nonlinear Einstein equations admit solutions which can be interpreted as gravitational waves?

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4. What is a definition of a gravitational **wave with nonplanar front** in the full theory?
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People: Hermann Bondi (1.11.1919-10.9.2005)

H. Bondi with P. Bergman (Warsaw 1962)

H. Bondi with L. Infeld (Warsaw 1962)

Bondi 1957 - Einstein and Rosen not right

Bondi H, *Plane gravitational waves in General relativity*, Nature, 179, (25.5.1957)

Plane Gravitational Waves in General Relativity

POLARIZED plane gravitational waves were first discovered by N. Rosen[1], who, however, came to the conclusion that such waves could not exist because the metric would have to contain certain physical singularities. More recent work by Taub[2] and McVittie[3] showed that there were no unpolarized plane waves, and this result has tended to confirm the view that true plane gravitational waves do not exist in empty space in general relativity. Partly owing to this, Scheidegger[4] and I[5] have both expressed the opinion that there might be no energy-carrying gravitational waves at all in the theory. It is therefore of interest to point out, as was first

It is therefore of interest to point out, as was first shown by Robinson[6] and has now been independently proved by me, that Rosen's argument is invalid and that true gravitational waves do in fact exist. Moreover, it is shown here that these waves carry energy, although it has not yet been possible to relate the intensity of the wave to the amount of energy carried.

H. BONDI

King's College, Strand,
London, W.C.2. March 24.

[1] Rosen, N., *Phys. Z. Sowjet Union*, **12**, 366 (1937). See also, Einstein, A., and Rosen, N., *J. Franklin Inst.*, **223**, 43 (1937).

[2] Taub, A. H., *Ann. Math.*, **53**, 472 (1951).

[3] McVittie, G. C., *J. Rational Mech. and Analysis*, **4**, 201 (1955).

[4] Scheidegger, A. E., *Rev. Mod. Phys.*, **25**, 451 (1953). See also Brdička, M., *Proc. Roy. Irish Acad.*, **54**, 137 (1951).

[5] Bondi, H., various contributions to discussions at the International Conference on Gravitation, Chapel Hill, N.C., 1957.

[6] Robinson, I. (to be published shortly).

[7] Pirani, F. A. E., *Phys. Rev.*, **105**, 1089 (1957).

[8] Lichnerowicz, A., "Théories relativistes de la gravitation et de l'électromagnétisme" (Paris, 1955).

People: Felix Pirani (2.2.1928-31.12.2015)

People: Ivor Robinson (7.10.1923-27.05.2016)

People: Ivor Robinson (7.10.1923-27.05.2016)

H. Bondi with I. Robinson (Warsaw 1962)

I. Robinson with A. Trautman (Trieste 1985)

Bondi, Pirani, Robinson 1958

Gravitational waves in general relativity
III. Exact plane waves

By H. Bondi* and F. A. E. Pirani†
King's College, London
and I. Robinson
Lately of University College of Wales, Aberystwyth

(*Communicated by W. H. McCrea, F.R.S.—Received* 18 *October* 1958)

Plane gravitational waves are here defined to be non-flat solutions of Einstein's empty space-time field equations which admit as much symmetry as do plane electromagnetic waves, namely, a 5-parameter group of motions. A general plane-wave metric is written down and the properties of plane wave space-times are studied in detail. In particular, their characterization as 'plane' is justified further by the construction of 'sandwich waves' bounded on both sides by (null) hyperplanes in flat space-time. It is shown that the passing of a sandwich wave produces a relative acceleration in free test particles, and inferred from this that such waves transport energy.

Bondi H, Pirani F A E, Robinson I *Gravitational waves in General relativity III. Exact plane waves*, Proc. R. Soc. London, ser. A, 251, (18.10.1958)

Bondi, Pirani, Robinson 1958

- motivated by the **analogy with electromagnetism**, where plane waves have a 5-dimensional group of symmetries they **defined a plane wave in the full GR theory** as a **solution** to the equations $Ric(g) = 0$, which **has precisely 5-dimensional group of symmetries**
- inspecting **Petrov**'s list of solutions to $Ric(g) = 0$ with high symmetries they found a unique class of solutions that have 5 symmetries; the class is given in terms of **one free complex function** $f = f(u)$, **differentiable in a real variable** u; the real and imaginary part of f is related to the **amplitude** and **polarization** of the wave, which therefore can be **modulated**
- this enables to produce waves of a **sandwich** type; they have shown that a **sandwich wave falling on a system of test particles affects their motion**, concluding that **plane waves carry energy**.

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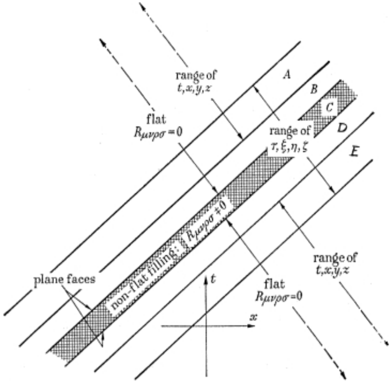

FIGURE 1. Arrangement of co-ordinate systems around sandwich wave.

Towards green lights

The Bondi - Pirani - Robinson paper solves our questions (1)-(3):

(1) What is a definition of a plane gravitational wave in the full theory? SOLVED!

(2) Does the so defined plane wave exist as a solution to the full Einstein system? YES!

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Einstein spaces which are mapped conformally on each other.

Von

H. W. Brinkmann in Cambridge (Mass., U. S. A.).

(47) $$ds^2 = 2dx\,dy + 2d\varphi\,d\theta + m\,d\varphi^2.$$

To this we apply the final equation (41b) which gives us $\frac{\partial^2 m}{\partial x\,\partial y} = 0$ so that

$$m = X(x, \varphi) + Y(y, \varphi).$$

The only surviving components of the Riemann tensor are here

$$R_{x\varphi\varphi x} = \frac{1}{2}\frac{\partial^2 X}{\partial x^2}, \qquad R_{y\varphi\varphi y} = \frac{1}{2}\frac{\partial^2 Y}{\partial y^2}$$

so that the V_4 is Euclidean if and only if

$$X = a_1 x + b_1, \qquad Y = a_2 y + b_2,$$

where a_1, b_1, a_2, b_2 are functions of φ.

Thus we can go on constructing Einstein spaces that can be mapped upon Einstein spaces in more and more ways.

(Eingegangen am 20. 7. 1924.)

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To this we apply the final equation (41 b) which gives us $\frac{\partial^2 m}{\partial x\,\partial y} = 0$ so that

$$m = X(x, \varphi) + Y(y, \varphi).$$

The only surviving components of the Riemann tensor are here

$$R_{x\varphi\varphi x} = \frac{1}{2}\frac{\partial^2 X}{\partial x^2}, \qquad R_{y\varphi\varphi y} = \frac{1}{2}\frac{\partial^2 Y}{\partial y^2}$$

so that the V_4 is Euclidean if and only if

$$X = a_1 x + b_1, \qquad Y = a_2 y + b_2,$$

where a_1, b_1, a_2, b_2 are functions of φ.

Thus we can go on constructing Einstein spaces that can be mapped upon Einstein spaces in more and more ways.

(Eingegangen am 20. 7. 1924.)

Brinkmann 1924

It was a **mathematician** H. W. Brinkman who **first** had a general solution to Einstein's equations which now is called **plane wave**. It was in *Einstein spaces which are mapped conformally on each other*, Mathem. Annalen, 94, (1925). Actually he had more general solution depending on a complex function $f = f(u, \zeta)$ holomorphic in complex variable ζ. This solution is called **pp-wave**. Plane wave is a special case! Totally **overlooked by the physicists!**

Einstein spaces which are mapped conformally on each other.

Von

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Closer to the green: Pirani 1957

Pirani F A E, *Invariant Formulation of Gravitational Radiation Theory*, Phys. Rev. 105, (18.10.1956)

PHYSICAL REVIEW VOLUME 105, NUMBER 3 FEBRUARY 1, 1957

Invariant Formulation of Gravitational Radiation Theory

F. A. E. Pirani
Department of Mathematics, King's College, Strand, London, England
(Received October 18, 1956)

In this paper, gravitational radiation is defined invariantly within the framework of general relativity theory. The definition is arrived at by assuming (*a*) that gravitational radiation is characterized by the Riemann tensor, and (*b*) that it is propagated with the fundamental velocity. Therefore a gravitational wave front should appear as a discontinuity in the Riemann tensor across a null 3-surface; the possible form of this discontinuity is here calculated from Lichnerowicz's continuity conditions.

The concept of an observer who follows the gravitational field is defined in terms of the eigenbivectors of the Riemann tensor. It is shown that the 4-velocity of this observer is timelike for one of Petrov's three canonical types of Riemann tensor, but null for the other two types. The first type is identified with the absence of radiation, the other two with its presence. This constitutes the definition. It is shown that the difference between the no-radiation type and one of the radiation types can be made to correspond to the discontinuity possible across a null 3-surface; this demonstrates the consistency of the wave front and following-the-field concepts.

A covariant approximation to the canonical energy-momentum pseudo-tensor is defined, using normal coordinates, which are given a physical interpretation. It is shown that when gravitational radiation is present, the approximate gravitational energy-flux cannot be removed by a local Lorentz transformation, which supports the definition of radiation.

It is proved that, as would be demanded of a sensible definition, there can be no gravitational radiation present in a region of empty space-time where the metric is static.

Pirani 1957

- **Pirani** had an **idea that radiative solutions of the Einstein's equations should be characterized by the properties of the curvature tensor** $Riemann(g)$ of the metric g;
- he postulated that the proper condition on $Riemann(g)$ is that in a radiative spacetime **it is algebraically special**, according to the **Petrov classification**
- Pirani did not know all **Petrov types**, which were spelled out in full generality by **Roger Penrose**, few years later; he did not made his statement precise: it was **unclear which Petrov type he attributes to gravitational radiation**
- also, Pirani postulated that radiative spacetimes should be algebraically special **everywhere**, which **was wrong**.

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Pirani 1957 - Petrov classification

Table 4.3. The roots of the algebraic equation (4.18) and their multiplicities

The corresponding multiplicities of the principal null directions are symbolically depicted on the right of this table.

Type	Roots E	Multiplicities
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D	$0,\ \infty$	(2,2)
II	$0,\ \pm \mathrm{i}\sqrt{\frac{3}{2}\lambda}$	(2,1,1)
III	$0,\ \infty$	(3,1)
N	0	(4)

Nowadays, due to our **next hero**, we know that a gravitational wave is of Petrov type N **far from the sources** (asymptotically).

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People: Andrzej Trautman

A. Trautman with S. Chandrasekhar (Warsaw 1973)

Green lights: Trautman 1958

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Série des sci. math., astr.
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THEORETICAL PHYSICS

Boundary Conditions at Infinity for Physical Theories

by

A. TRAUTMAN

Presented by L. INFELD on April 12, 1958

1. The Cauchy problem is the most natural for hyperbolic partial differential equations. When dealing with physical problems, we are, however, often interested in solutions of field equations with given sources when nothing is known about initial conditions. A whole set of fields corresponds, in general, to given sources and, in order to arrive at a unique solution of the problem, we must specify some additional condition. For linear field equations this condition may consist in prescribing the form of Green's function (e. g. retarded, advanced, etc.). If we investigate the field in the whole (unbounded) space-time we can ensure uniqueness by specifying some appropriate *boundary conditions* at spatial infinity. The latter approach has the advantage of being applicable to non-linear theories, such as the theory of general relativity. These boundary conditions, first formulated for a periodic scalar field by Sommerfeld [1], have a definite physical meaning. E. g., the "Ausstrahlungsbedingung" of Sommerfeld means that the system can lose its energy in the form of radiation and that no waves are falling on the system from the exterior.

The purpose of this paper is to formulate boundary conditions for scalar and Maxwell theories in a form which exhibits their physical meaning and is proper to a generalization for the gravitational case.

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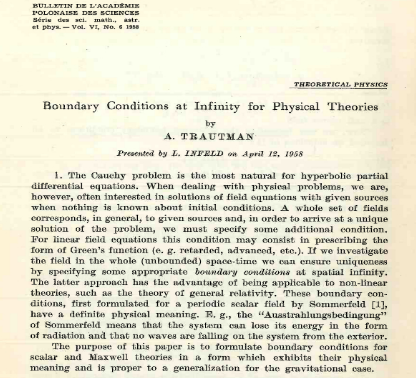

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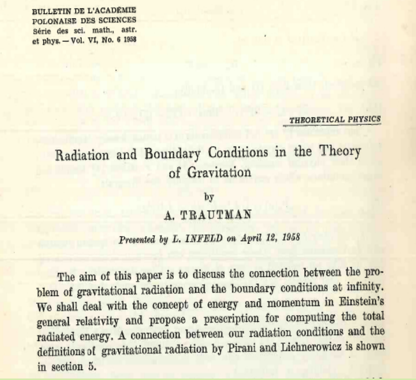

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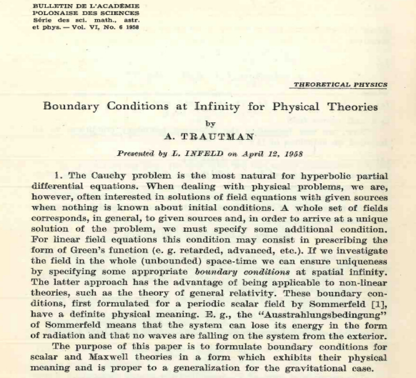

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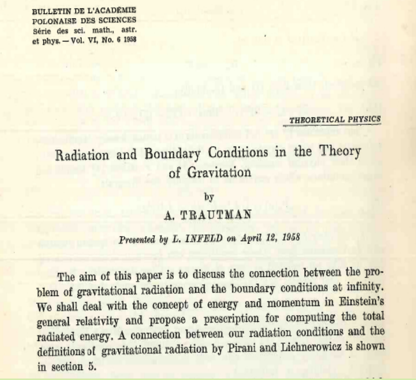

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In these two papers Trautman solves our red light problems:

(4) What is a definition of a gravitational wave with nonplanar front in the full theory?

(5) What is the energy of such waves ?

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- **Trautman's idea**: from all solutions of vacuum Einstein equations **select those that satisfy suitable boundary conditions at infinity**
- apropriately **reformulate boundary conditions for radiative solutions of the relativistic wave equation for a scalar field** known as **Sommerfeld's radiation conditions** (Courant, Hilbert, Methods of Mathematical Physics, vol.2, p. 315)
- if this is done properly, then **such conditions can be** straightforwardly **defined in nonlinear theories**, in particular in GR.

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Trautman 1958: gravitational waves - DEFINITION

- In it Trautman defines the **boundary conditions for a radiative spacetime in full GR theory**. This is a **definition of gravitational radiation**. This is in [2], on p. 409, equations (9) and (10).

We generalize the conditions of Fock along the lines presented in the preceding paper. First, introduce a null vector field k, defined as follows. Let n^ν be a unit space-like vector lying in σ, perpendicular to the "sphere" $r = \text{const.}$, and pointing outside it. We put $k^\nu = n^\nu + t^\nu$, where t denotes a unit time-like vector normal to σ, such that $t^0 > 0$.

Now, we formulate the following boundary conditions to be imposed on gravitational fields due to isolated systems of matter: *there exist co-ordinate systems and functions* $h_{\mu\nu} = O(r^{-1})$ *such that*

(9) $$g_{\mu\nu} = \eta_{\mu\nu} + O(r^{-1}), \quad g_{\mu\nu,\varrho} = h_{\mu\nu} k_\varrho + O(r^{-2}),$$

(10) $$(h_{\mu\nu} - \tfrac{1}{2}\eta_{\mu\nu}\eta^{\varrho\sigma}h_{\varrho\sigma})k^\nu = O(r^{-2}).$$

These conditions correspond to Sommerfeld's "Ausstrahlungsbedingung"; we obtain the "Einstrahlungsbedingung" assuming n^ν to be a normal pointing inward the sphere $r = \text{const.}$ Relations (9), (10) are

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A **spacetime contains radiation**, if sufficiently far from the sources, it admits a coordinate system x^μ in which

- the metric coefficients behave as $g_{\mu\nu} = \eta_{\mu\nu} + \mathcal{O}(1/r)$, with r being one of the coordinates x^μ interpreted as an affine parameter along geodesics escaping to infinity (spatial or null)
- metric's first derivatives behave as $g_{\mu\nu,\rho} = v_{\mu\nu} k_\rho + \mathcal{O}(1/r^2)$ with a null vector k^μ, and with $v_{\mu\nu} = \mathcal{O}(1/r)$
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- the coordinate system is assymptotically harmonic $\Box x^\mu = \mathcal{O}(1/r^2)$.

Trautman 1958 - remarks on boundary conditions

Lichnerowicz:

Let us take an isolated system of masses ($T_{\mu\nu} = 0$ outside a bounded 3-region) and assume the existence of co-ordinates such that [5]

$$g_{\mu\nu} = \eta_{\mu\nu} + O(r^{-1}), \quad g_{\mu\nu,\varrho} = O(r^{-2}), \tag{6}$$

where r denotes the distance measured along geodesics from a fixed point on a space-like σ. Eqs. (6) have a double meaning: they constitute a sy-

Trautman:

We generalize the conditions of Fock along the lines presented in the preceding paper. First, introduce a null vector field k, defined as follows. Let n^ν be a unit space-like vector lying in σ, perpendicular to the "sphere" $r = \text{const.}$, and pointing outside it. We put $k^\nu = n^\nu + t^\nu$, where t denotes a unit time-like vector normal to σ, such that $t^0 > 0$.

Now, we formulate the following boundary conditions to be imposed on gravitational fields due to isolated systems of matter: *there exist co-ordinate systems and functions* $h_{\mu\nu} = O(r^{-1})$ *such that*

$$g_{\mu\nu} = \eta_{\mu\nu} + O(r^{-1}), \quad g_{\mu\nu,\varrho} = h_{\mu\nu} k_\varrho + O(r^{-2}), \tag{9}$$

$$(h_{\mu\nu} - \tfrac{1}{2}\eta_{\mu\nu}\eta^{\varrho\sigma}h_{\varrho\sigma})k^\nu = O(r^{-2}). \tag{10}$$

These conditions correspond to Sommerfeld's "Ausstrahlungsbedingung"; we obtain the "Einstrahlungsbedingung" assuming n^ν to be a normal pointing inward the sphere $r = \text{const.}$ Relations (9), (10) are

Trautman 1958 - reformulation of Einstein's equations

not depend on σ. As is known, in general relativity the energy-momentum tensor of matter $\mathfrak{T}_{\mu\nu}$ does not by itself lead to an integral conservation law. However, if we introduce an energy-momentum pseudotensor of the gravitational field $\mathfrak{t}_\mu^\nu = (\delta_\mu^\nu \mathfrak{G} + g^{\varrho\sigma}{}_{,\mu}\partial\mathfrak{G}/\partial g^{\varrho\sigma}{}_{,\nu})/2\varkappa$, then the sum $\mathfrak{T}_\mu^\nu + \mathfrak{t}_\mu^\nu$ is divergenceless by virtue of Einstein's equations *). Einstein's tensor density $\mathfrak{G}^\nu{}_\mu = \sqrt{-g}(R_\mu^\nu - \frac{1}{2}\delta_\mu^\nu R)$ can namely be written in the form

$$\mathfrak{G}_\mu^\nu \equiv \varkappa(\mathfrak{t}_\mu^\nu + \mathfrak{U}_\mu^{\lambda\nu}{}_{,\lambda}), \tag{1}$$

where the "superpotentials" $\mathfrak{U}_\mu^{\nu\lambda}$ are given in [1]

$$2\varkappa\mathfrak{U}_\mu^{\nu\lambda} \equiv \sqrt{-g}\, g^{\sigma[\varrho}\delta_\mu^\nu g^{\lambda]\tau} g_{\varrho\sigma,\tau} \equiv -2\varkappa\mathfrak{U}_\mu^{\lambda\nu}. \tag{2}$$

If the Einstein equations

$$G_{\mu\nu} = -\varkappa T_{\mu\nu} \tag{3}$$

are satisfied, then Eqs. (1) and (2) imply

$$\mathfrak{T}_\mu^\nu + \mathfrak{t}_\mu^\nu = \mathfrak{U}_\mu^{\nu\lambda}{}_{,\lambda}, \quad \text{thus} \quad (\mathfrak{T}_\mu^\nu + \mathfrak{t}_\mu^\nu)_{,\nu} = 0. \tag{4}$$

The functions $\mathfrak{t}_\mu^\nu$ are not components of a tensor density (equivalence principle) and many physicists (e. g., Schrödinger [2]) have raised doubts

Trautman 1958 - energy-momentum of pure gravity

- uses **Freud potential** 2-form $\mathcal{F}$, to split the Einstein tensor $E = Ric(g) - \frac{1}{2}Rg$ into $E = \mathrm{d}\mathcal{F} - 8\pi t$ so that **the Einstein equations** $E = 8\pi T$ **take the form**

$$\boxed{\mathrm{d}\mathcal{F} = 8\pi(T + t)}.$$

  Here T is the energy-momentum 3-form.
- Since t **is a 3-form totally determined by the geometry**, he **interprets it as an energy-momentum 3-form of a PURE GRAVITY**. This is in [2], on p. 407, equations (1) and (2).

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- uses the closed 3-form $T + t$ to **define a 4-momentum** $P_\mu(\sigma)$ **of GRAVITATIONAL FIELD attributed to each space-like hypersurface** σ **of a space-time satisfying his radiative boundary conditions**, [2], p. 408, equation (5).

The functions $t_\mu^{\ \nu}$ are not components of a tensor density (equivalence principle) and many physicists (e. g., Schrödinger [2]) have raised doubts as to their physical meaning. Einstein [3] and F. Klein [4] formulated some conditions which enable us to consider the integrals

$$P_\mu[\sigma] = \int_\sigma (\mathfrak{T}_\mu^{\ \nu} + t_\mu^{\ \nu})\, dS_\nu = \oint_S \mathfrak{U}_\mu^{\ \nu\lambda}\, dS_{\nu\lambda} \tag{5}$$

as representing the total energy and momentum of the system: matter and gravitational field. These conditions can be summarized as follows.

- shows that
  - $P_\mu(\sigma)$ **is finite** and
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Trautman 1958: precursor of BMS group

Let us take a co-ordinate transformation

$$x^\nu \to x'^\nu = x^\nu + a^\nu(x) \tag{11}$$

fulfilling

$$a^\nu = o(r)\,, \qquad a_{\nu,\mu} = b_\nu k_\mu + O(r^{-2}) \tag{12}$$

where

$$a_\nu = \eta_{\nu\mu} a^\mu\,, \qquad b_\nu = O(r^{-1})\,,$$

and

$$a_{\nu,\mu\varrho} = b_{\nu,\mu} k_\varrho + O(r^{-2})\,, \qquad b_{\nu,\varrho} = O(r^{-1})\,. \tag{13}$$

From (13) follows the existence of functions $c_\nu = O(r^{-1})$ such that

$$b_{\nu,\mu} = c_\nu k_\mu + O(r^{-2})\,. \tag{14}$$

Co-ordinate transformations (11) satisfying (12) and (13) preserve the form of our boundary conditions; this can be easily seen from the transformation formulae for $g_{\mu\nu}$ and $h_{\mu\nu}$:

$$\begin{aligned} g'_{\mu\nu}(x') &\cong g_{\mu\nu}(x) + b_\mu k_\nu + b_\nu k_\mu\,, \\ h'_{\mu\nu}(x') &\cong h_{\mu\nu}(x) + c_\mu k_\nu + c_\nu k_\mu\,. \end{aligned} \tag{15}$$

Computing the superpotentials in both co-ordinate systems and taking into account the relations (9)-(15) we obtain

$$\mathfrak{U}_\mu'^{\nu\lambda} k'_\nu n'_\lambda = \mathfrak{U}_\mu^{\nu\lambda} k_\nu n_\lambda + O(r^{-3})\,.$$

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- **calculates** precisely **how much of the gravitational energy** $p_\mu = P_\mu(\sigma_1) - P_\mu(\sigma_2)$ contained between the spacelike hypersurfaces σ_1 (initial one) and σ_2 (final one) **escapes to infinity** - or, in nowadays **Penrose's** terminology - **to scri**, [2], p.410-411, equations (16)-(17).
- shows that p_0 **is NON-negative**, [2], p. 411, remark after (17). **Weak** proof, because he is only able to prove $p_0 \geqslant 0$.

4. The total energy and momentum p_μ radiated between two hypersurfaces σ and σ' is given by (7), or by

$$p_\mu = P_\mu[\sigma] - P_\mu[\sigma'] = \int_\Sigma \mathfrak{t}_\mu{}^\nu dS_\nu$$

($T_{\mu\nu}$ vanishes on Σ). The boundary conditions enable the estimation of p_μ; we have, indeed,

(16) $$\mathfrak{t}_\mu{}^\nu = \tau k_\mu k^\nu + O(r^{-3}),$$

where

(17) $$4\varkappa\tau = h^{\mu\nu}(h_{\mu\nu} - \tfrac{1}{2}\eta_{\mu\nu}\eta^{\varrho\sigma}h_{\varrho\sigma}).$$

τ is invariant with respect to transformation (15) and is *non-negative* by virtue of (10); therefore $p_0 \geqslant 0$. The existence of radiation is characterized by $p_\mu \neq 0$.

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Moreover, it follows from (19) that

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Almost everything green

After Trautman's paper [2]:

(4) What is a definition of a gravitational wave with nonplanar front in the full theory? SOLVED!

(5) What is the energy of such waves ? SOLVED!

What is missing is **to find at least one example of an exact solution to** $Ric(g) = 0$, **satisfying Trautman's boundary conditions, and having** $p_0 > 0$.

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VOLUME 4, NUMBER 8 PHYSICAL REVIEW LETTERS APRIL 15, 1960

SPHERICAL GRAVITATIONAL WAVES*

Ivor Robinson
Department of Physics, University of North Carolina, Chapel Hill, North Carolina,

and

A. Trautman
Institute of Physics, Polish Academy of Science, Warsaw, Poland†
(Received March 7, 1960; revised manuscript received March 24, 1960)

If these equations are satisfied, the curvature tensor may be written as

$$R_{ijkl} = \rho^{-3} D_{ijkl} + \rho^{-2} \mathrm{III}_{ijkl} + \rho^{-1} N_{ijkl},$$

where D_{ijkl}, III_{ijkl}, and N_{ijkl} are tensors of type I degenerate, type III, and type II null, respectively. They are covariantly constant on any ray of constant σ, ξ, η.

The solution is degenerate type I if m is non-

Further consequences: Syracuse 1961

In 1961 P. Bergmann, A. Trautman, R. Penrose, J. Goldberg, R. Sachs, E. T. Newman, E. Schucking, and others met in Syracuse NY (nowadays it would be called one year postdoc) , where a lot of the development happened.

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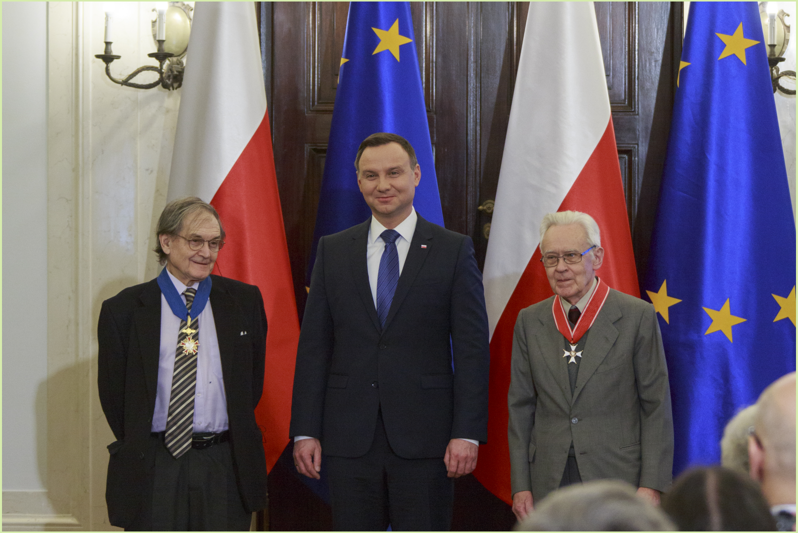

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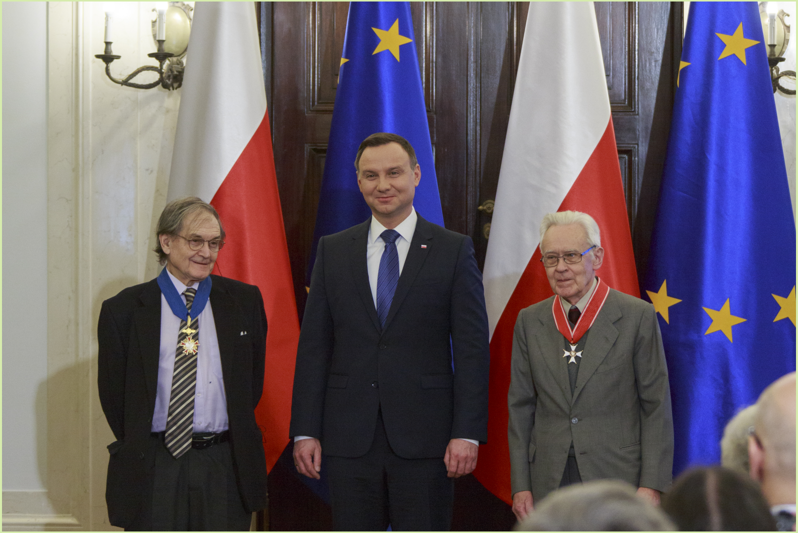

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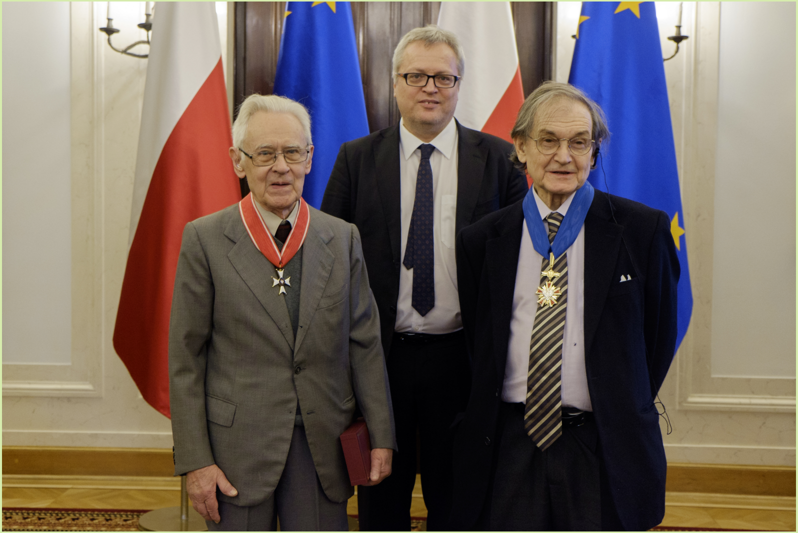

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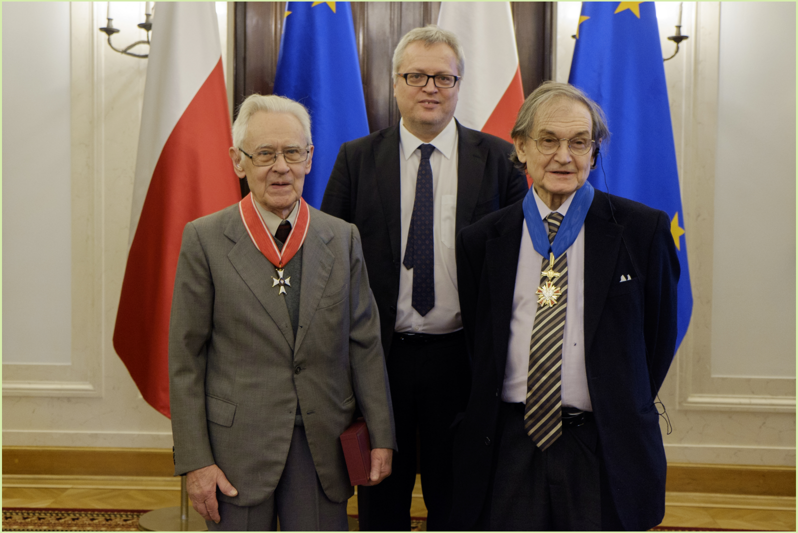

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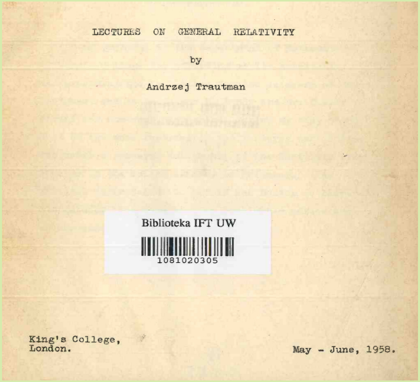

LECTURES ON GENERAL RELATIVITY

by

Andrzej Trautman

King's College,
London.

May - June, 1958.

Trautman 1958 - King's College London Lectures

ACKNOWLEDGEMENTS

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