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Is there the radion in the RS2 model ?

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Abstract

We analyse the physical boundary conditions at infinity for metric fluctuations and gauge functions in the RS2 model with matter on the brane. We argue that due to these boundary conditions the radion field cannot be gauged out in this case. Thus, it represents a physical degree of freedom of the model.

1 Introduction

The RS2 model [1] is based on the solution for the background metric, which was obtained from the solution for the background metric of the Randall-Sundrum model with two branes [2] by pushing the negative tension brane to infinity. The model describes gravity in a five-dimensional space-time E with one brane embedded into it. We denote the coordinates in E by $\{x^M\} \equiv \{x^\mu, x^4\}$, $M = 0,1,2,3,4$, $\mu = 0,1,2,3$, the coordinate $x^4 \equiv y$ parameterizing the fifth dimension, which is infinite. The brane is located at $y = 0$, and all the fields possess a symmetry under the reflection $y \leftrightarrow -y$, which is inherited from the RS1 model. Explicitly, it reads

$$\begin{aligned} g_{\mu\nu}(x,-y) &= g_{\mu\nu}(x,y), \\ g_{\mu 4}(x,-y) &= -g_{\mu 4}(x,y), \\ g_{44}(x,-y) &= g_{44}(x,y). \end{aligned} \tag{1}$$

The meaning of this symmetry can be easily understood even without referring to the RS1 model: if matter is localized on the brane, all the physical fields should possess a symmetry under the reflection in the brane.

It is a common knowledge that among the degrees of freedom of the RS1 model there is a massless scalar field, called the radion and describing the oscillations of the branes with respect to each other. At the first glance, it seems to be very likely that this degree of freedom should drop from the model, if one brane is pushed to infinity. In fact, this assumption was made in papers [1, 6, 7], where it was noted that the 44-component of the metric fluctuations, which corresponds to the scalar mode, could be gauged out. However, in this gauge the brane is located not at $y = 0$, but at $y = \xi(x)$. Obviously, this "bent-brane" formulation destroys the reflection symmetry (1), which makes the approach based on this gauge inconsistent; this fact was noted in [8]. In paper [5] it was observed that gauging out the radion field in the straight brane formulation with matter on the brane leads to unphysical solutions, which diverge at infinity. Thus, gauging out the radion field resulted in some discrepancies, and it looks as if this field were of particular importance in the RS2 model. In the present paper we are going to study the role of the radion in the RS2 model more thoroughly. We begin with briefly discussing the main features of the RS2 model.

The action of the model is

$$S = S_g + S_{brane}, \tag{2}$$

where S_g and S_{brane} are given by

$$\begin{aligned} S_g &= \frac{1}{16\pi\hat{G}}\int_E (R-\Lambda)\sqrt{-g}\, d^4x dy, \\ S_{brane} &= V\int_E \sqrt{-\tilde{g}}\delta(y) d^4x dy. \end{aligned} \tag{3}$$

Here $\tilde{g}_{\mu\nu}$ is the induced metric on the brane and V is the brane tension. We also note that the signature of the metric g_{MN} is chosen to be $(-,+,+,+,+)$.

The Randall-Sundrum solution for the metric is given by

$$ds^2 = g_{MN}dx^M dx^N = e^{2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \tag{4}$$

where $\eta_{\mu\nu}$ is the Minkowski metric and the function $\sigma(y) = -k|y|$. The parameter k is positive and has the dimension of mass; the parameters Λ and V are related to it as follows:

$$\Lambda = -12k^2, \quad V = -\frac{3k}{4\pi\hat{G}}.$$

We see that the brane has a positive energy density. The function σ has the properties

$$\partial_4\sigma = -k\, sign(y), \quad \frac{\partial^2\sigma}{\partial y^2} = -2k\delta(y). \tag{5}$$

Here and in the sequel $\partial_4 \equiv \frac{\partial}{\partial y}$.

We denote $\hat{\kappa} = \sqrt{16\pi\hat{G}}$, where $\hat{G}$ is the five-dimensional gravitational constant, and parameterize the metric g_{MN} as

$$g_{MN} = \gamma_{MN} + \hat{\kappa}h_{MN}, \tag{6}$$

h_{MN} being the metric fluctuations. Substituting this parameterization into (2) and retaining the terms of the zeroth order in $\hat{\kappa}$, we can get the second variation action of this model. In [3] the second variation action for the RS1 model was obtained, and we can apply this result to the RS2 model just by changing the definition of $\sigma(y)$ and of its derivatives.

The action is invariant under the gauge transformations

$$h'_{MN}(x,y) = h_{MN}(x,y) - (\nabla_M\xi_N(x,y) + \nabla_N\xi_M(x,y)), \tag{7}$$

where ∇_M is the covariant derivative with respect to the background metric γ_{MN}, and the functions $\xi^M(x,y)$ satisfy the symmetry conditions

$$\begin{aligned}\xi^{\mu}(x,-y) &= \xi^{\mu}(x,y) \\ \xi^{4}(x,-y) &= -\xi^{4}(x,y)\,.\end{aligned} \tag{8}$$

Equations (7) can be rewritten in a more useful component form as follows:

$$h'_{\mu\nu}(x) = h_{\mu\nu}(x) - (\partial_\mu \xi_\nu + \partial_\nu \xi_\mu + 2\gamma_{\mu\nu}\partial_4\sigma\xi_4)\,, \tag{9}$$

$$h'_{\mu 4}(x) = h_{\mu 4}(x) - (\partial_\mu \xi_4 + \partial_4 \xi_\mu - 2\partial_4\sigma\xi_\mu)\,, \tag{10}$$

$$h'_{44}(x) = h_{44}(x) - 2\partial_4\xi_4. \tag{11}$$

2 Gauge conditions and equations of motion for linearized gravity

Now let us discuss the gauge conditions and equations of motion for linearized gravity in the presence of matter on the brane. The interaction with matter on the brane has the standard form

$$\frac{\hat{\kappa}}{2}\int_{brane} h^{\mu\nu}(x,0)t_{\mu\nu}(x)dx, \tag{12}$$

$t_{\mu\nu}(x)$ denoting the energy-momentum tensor of the matter.

First, we would like to emphasize that in general all fluctuations of metric must satisfy the physical boundary conditions at $y \to \pm\infty$, $x^i \to \pm\infty \quad (i = 1,2,3)$, i.e. vanish at spatial infinity. This is a reasonable assumption - for example, the h_{00}-component is associated with Newton's potential, which must vanish at infinity (for the matter, which is localized in some finite domain). Below we will show that the fields of certain exact solutions (for example, with point-like matter sources) do satisfy these boundary conditions.

Obviously, the gauge functions $\xi^M(x,y)$ must be finite everywhere in E. This means that

$$\xi_\mu = e^{2\sigma}\eta_{\mu\nu}\xi^\nu|_{y\to\pm\infty} \to 0.$$

The situation with ξ_4 is more complicated, since $\xi_4 = g_{44}\xi^4 = \xi^4$. Let us consider equation (10). It follows from this equation that if ξ_4 does not depend on four-dimensional coordinates x, we can satisfy the physical boundary condition for the field $h_{\mu 4}$ without requiring ξ_4 to vanish at $y \to \pm\infty$. But in this case the last term in the r.h.s. of (9) does not satisfy the physical boundary condition for the field $h_{\mu\nu}$ at $x^i \to \pm\infty$. This means that ξ_4 must be x-dependent and vanish at $x^i \to \pm\infty$. At the same time the form of the second term in the r.h.s. of (10) shows that ξ_4 must vanish at $y \to \pm\infty$ to satisfy the physical boundary conditions for the field $h_{\mu 4}$. Thus, we have the following boundary conditions for ξ_M:

$$\xi_M|_{x^i,y\to\pm\infty} \to 0 \tag{13}$$

Now let us examine the equations of motion. They look as follows:

1) $\mu\nu$-component

$$
\begin{aligned}
&\frac{1}{2}\left(\partial_\rho\partial^\rho h_{\mu\nu} - \partial_\mu\partial^\rho h_{\rho\nu} - \partial_\nu\partial^\rho h_{\rho\mu} + \partial_4\partial_4 h_{\mu\nu}\right) - \\
- \quad & 2k^2 h_{\mu\nu} + \frac{1}{2}\partial_\mu\partial_\nu\tilde{h} + \frac{1}{2}\partial_\mu\partial_\nu h_{44} - \partial_4\sigma(\partial_\mu h_{\nu 4} + \partial_\nu h_{\mu 4}) - \frac{1}{2}\partial_4(\partial_\mu h_{\nu 4} + \partial_\nu h_{\mu 4}) + \\
+ \quad & \frac{1}{2}\gamma_{\mu\nu}\Big(\partial^\rho\partial^\sigma h_{\rho\sigma} - \partial_\rho\partial^\rho\tilde{h} - \partial_4\partial_4\tilde{h} - 4\partial_4\sigma\partial_4\tilde{h} - \partial_\rho\partial^\rho h_{44} + 12k^2 h_{44} + 3\partial_4\sigma\partial_4 h_{44} + \\
+ \quad & 2\partial^\rho\partial_4 h_{\rho 4} + 4\,\partial_4\sigma\partial^\rho h_{\rho 4}\Big) + \left(2kh_{\mu\nu} - 3k\gamma_{\mu\nu}h_{44}\right)\delta(y) = -\frac{\hat{\kappa}}{2}t_{\mu\nu}(x)\delta(y),
\end{aligned}
\tag{14}
$$

2) $\mu 4$-component

$$
\partial_4(\partial_\mu\tilde{h} - \partial^\nu h_{\mu\nu}) - 3\partial_4\sigma\partial_\mu h_{44} - \partial^\nu\left(\partial_\mu h_{\nu 4} - \partial_\nu h_{\mu 4}\right) = 0, \tag{15}
$$

3) 44-component

$$
\frac{1}{2}(\partial^\mu\partial^\nu h_{\mu\nu} - \partial_\mu\partial^\mu\tilde{h}) - \frac{3}{2}\partial_4\sigma\partial_4\tilde{h} + 6k^2 h_{44} + 3\partial_4\sigma\partial^\mu h_{\mu 4} = 0, \tag{16}
$$

where $\tilde{h} = \gamma^{\mu\nu}h_{\mu\nu}$.

In what follows, we will also use an auxiliary equation, which is obtained by multiplying the equation for 44-component by 2 and subtracting it from the contracted equation for $\mu\nu$-component. This equation contains $\tilde{h}$, $h_{\mu 4}$ and h_{44} only and has the form:

$$
\partial_4\left(e^{2\sigma}\partial_4\tilde{h}\right) - 4\partial_4\left(e^{2\sigma}\partial_4\sigma h_{44}\right) - 2\partial_4(e^{2\sigma}\partial^\mu h_{\mu 4}) + \Box h_{44} = \frac{\hat{\kappa}}{3}t^\mu_\mu(x)\delta(y), \tag{17}
$$

where $\Box = \eta^{\mu\nu}\partial_\mu\partial_\nu$. By integrating this equation in the limits $(-\infty, \infty)$ and using the physical boundary conditions for the fields $h_{\mu\nu}$, $h_{\mu 4}$ and h_{44}, we find that the function $\varphi(x)$, defined by

$$
\int_{-\infty}^{\infty} h_{44}(y)\,dy = \varphi(x), \tag{18}
$$

is not equal to zero and satisfies the equation

$$
\Box\varphi(x) = \frac{\hat{\kappa}}{3}\,\eta^{\mu\nu}t_{\mu\nu}(x) \equiv \frac{\hat{\kappa}}{3}\,t(x). \tag{19}
$$

Obviously, the admissible gauge transformations do not alter the physical boundary conditions for the metric fluctuations, and therefore equation (19) holds in any gauge. This is an equation for a four-dimensional scalar field, which coincides with the equation for the radion field in the RS1 model with matter on the positive tension brane [4].

Thus, we arrive at the corollary that the radion field cannot be gauged out in the RS2 model, because otherwise the equations of motion for linearized gravity become inconsistent. In other words, this means that the gauge functions ξ_4, corresponding to the gauge $h_{44} = 0$, do not satisfy the boundary conditions at $y \to \pm\infty$, which is a good check of the consistency of our approach. In fact, this was noted in [5]. It was shown there that the solutions for the linearized gravity in the absence of the radion are unphysical, i.e. they diverge at $y = \pm\infty$.

We will use the following form of ξ_4 to impose an appropriate gauge on the field h_{44}:

$$\xi_4(x,y) = \frac{1}{4}\int_{-y}^{y} h_{44}(x,y')dy' - \frac{1}{4C}\int_{-y}^{y} F(y')dy' \int_{-\infty}^{\infty} h_{44}(x,y')dy', \tag{20}$$

where $F|_{y\to\pm\infty} = 0$ and

$$C = \int_{-\infty}^{\infty} F(y)dy. \tag{21}$$

Note that ξ_4 satisfies the symmetry and the boundary conditions. With the help of (20) we can pass to the gauge, in which

$$h_{44}(x,y) = F(y)\phi(x), \tag{22}$$

where

$$\phi(x) = \frac{1}{C}\int_{-\infty}^{\infty} h_{44}(x,y)dy \tag{23}$$

and depends on x only. It turns out to be convenient to choose $F(y) = e^{2\sigma} = e^{-2k|y|}$. Obviously, the field h_{44} satisfies the symmetry and the physical boundary conditions in this gauge. Moreover, we have no residual gauge transformations with ξ_4. We also note that since $\xi_4(x,0) = 0$, the brane remains straight in this gauge, i.e. we *do not* use the bent-brane formulation [6, 7], which allegedly destroys the structure of the model (this problem was discussed in [8]).

We would like to note that the gauge choice of the type (22) with an arbitrary finite even function $F(y)$ can be used it the RS1 model as well. For example, a gauge with $h_{44}(x,y) \sim e^{2k|y|}\phi(x)$ was used in [9].

Now let us discuss the gauge condition for the field $A_\mu = h_{\mu4}$. Let us take the gauge function $\xi_\mu(x,y)$ in the following form:

$$\xi_\mu(x,y) = e^{2\sigma}\int_{-\infty}^{y} e^{-2\sigma} A_\mu\left(x^\nu, y'\right) dy'. \tag{24}$$

Of course, this definition makes sense, if the field A_μ is such that the integral in (24) is well convergent to provide an acceptable ($\sim e^{2\sigma}$) decrease of ξ_μ. One can easily see that due to the symmetry $A_\mu(x,-y) = -A_\mu(x,y)$ (see (1)), $\xi_\mu(x,y)$ satisfies the symmetry condition $\xi_\mu(x,-y) = \xi_\mu(x,y)$. Moreover, it is easy to see that $\xi_\mu(x,y)|_{y\to\pm\infty} \to 0$, at least in the sense of the principal value of the integral in eq. (24) (again due to the symmetry of A_μ). Finally, it is not difficult to check that the gauge transformation with ξ_μ given by (24) gauges the field A_μ out.

We think that this formal argumentation can be used in favor of the possibility to make the A_μ-field vanish everywhere. Moreover, with a different motivation, an expression similar to (24) was assumed to be well defined in [8]. Anyway, in all the papers concerning the RS2 model it is universally recognized that the field A_μ can be gauged away (see, for example, [5]). Thus, we also adhere to this opinion. As we will see later, equations of motion can be solved exactly in the gauge $A_\mu = 0$ (see also [5]).

After this gauge fixing we are still left with residual gauge transformations of the form

$$\partial_4\left(e^{-2\sigma}\xi_\mu\right) = 0. \tag{25}$$

Now we are ready to solve equations of motion in the gauge

$$\begin{aligned} h_{\mu 4}(x,y) &= 0, \\ h_{44}(x,y) &= e^{2\sigma}\phi(x). \end{aligned} \tag{26}$$

3 Solution of the equations of motion

The substitution, which allows us to solve equations of motion in the gauge (26), has the form

$$h_{\mu\nu} = b_{\mu\nu} + \frac{1}{2}\, e^{2\sigma}\gamma_{\mu\nu}\phi - \frac{1}{2k^2}\,\sigma\, e^{2\sigma}\partial_\mu\partial_\nu\phi. \tag{27}$$

Note that if $b_{\mu\nu}|_{y\pm\to\infty} \to 0$, then $h_{\mu\nu}|_{y\pm\to\infty} \to 0$. Substituting (27) into (15), (16), (17) and using the notation $\tilde{b} = \gamma^{\mu\nu} b_{\mu\nu}$, similar to the one utilized in (15), (16), we get

$$\partial_4(\partial_\mu \tilde{b} - \partial^\nu b_{\mu\nu}) = 0, \tag{28}$$

$$(\partial^\mu\partial^\nu b_{\mu\nu} - \partial_\mu\partial^\mu\tilde{b}) - 3\partial_4\sigma\partial_4\tilde{b} = 0, \tag{29}$$

$$\partial_4\left(e^{2\sigma}\partial_4\tilde{b}\right) + \frac{1}{k}\,\Box\,\phi\delta(y) = \frac{\hat{\kappa}}{3}\, t^\mu_\mu(x)\delta(y). \tag{30}$$

Integrating (30) in the limits $(-\infty,\infty)$ and using the physical boundary conditions for the field $b_{\mu\nu}$, we get

$$\Box\,\phi = \frac{\hat{\kappa}k}{3} t. \tag{31}$$

This mean that

$$\partial_4\tilde{b} = B(x)\, e^{-2\sigma}, \tag{32}$$

where $B(x)$ is some function of x only. Using the symmetry conditions (1), we obtain $B(x) \equiv 0$.

Recall that we have at our disposal the gauge transformations satisfying (25). With the help of these transformations, we can impose the gauge

$$\tilde{b} = b = 0, \tag{33}$$

where $b = \eta^{\mu\nu} b_{\mu\nu}$. It is easy to see that there remain gauge transformations parameterized by $\xi_\mu = e^{2\sigma}\epsilon_\mu(x)$ with $\epsilon_\mu(x)$ satisfying $\partial^\mu\epsilon_\mu = 0$. Substituting expression (33) into (28) and (29) we arrive at the following system of relations:

$$\partial^\mu\partial^\nu b_{\mu\nu} = 0, \tag{34}$$

$$\partial_4(e^{-2\sigma}\partial^\mu b_{\mu\nu}) = 0, \tag{35}$$

where indices are raised with flat Minkowski metric $\eta^{\mu\nu}$. The remaining gauge transformations are sufficient to impose the condition

$$\partial^\mu b_{\mu\nu} = 0. \tag{36}$$

The conditions (33) and (36) define the gauge, which is usually called the transverse-traceless (TT) gauge. Having imposed this gauge, we are still left with residual gauge transformations

$$\xi_\mu = e^{2\sigma}\epsilon_\mu(x), \quad \Box\epsilon_\mu = 0, \quad \partial^\mu\epsilon_\mu = 0, \tag{37}$$

which are important for determining the number of degrees of freedom of the massless mode of $b_{\mu\nu}$.

Substituting (27) into (14) and using (33), (36) and (31), we get the well-known equation

$$\begin{aligned}\frac{1}{2}\left(e^{-2\sigma}\Box\, b_{\mu\nu} + \partial_4\partial_4 b_{\mu\nu}\right) - 2k^2 b_{\mu\nu} + 2k b_{\mu\nu}\delta(y) = \\ = -\frac{\hat\kappa}{2}\,\delta(y)\left[t_{\mu\nu} - \frac{1}{3}\left(\eta_{\mu\nu} - \frac{\partial_\mu\partial_\nu}{\Box}\right)t\right].\end{aligned} \tag{38}$$

This equation is identical to the one obtained by Garriga and Tanaka [6]. It was solved exactly, for example, in [8], and the solution for ordinary (not tachyonic) matter on the brane looks like

$$b_{\mu\nu}(x,y) = \frac{1}{(2\pi)^4}\int_{p^2>0} e^{-i\eta_{\mu\nu}p^\mu x^\nu}\tilde b_{\mu\nu}(p,y)d^4p, \tag{39}$$

where for $p^2 = -p_0^2 + \vec p^{\,2} > 0$ (which includes the static case $p_0 = 0$)

$$\tilde b_{\mu\nu}(p,y) = \left[\tilde t_{\mu\nu} - \frac{1}{3}\left(\eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right)\tilde t\,\right]\frac{\hat\kappa}{2\sqrt{p^2}}\,\frac{K_2\left(\frac{\sqrt{p^2}}{k}e^{k|y|}\right)}{K_1\left(\frac{\sqrt{p^2}}{k}\right)}. \tag{40}$$

We note, that (40) coincides with the corresponding formula for the RS1 model, obtained in [4], in the limit $R \to \infty$.

Thus, the exact solution for linearized gravity in our gauge is given by (27), (33), (36), (31), (39) and (40). Taking into account, that ϕ does not depend on the extra coordinate y and using (27), (39), (40) one can easy see that with a "good" energy-momentum tensor $t_{\mu\nu}(x)$ (for example, that of a static point-like source) fields $h_{\mu\nu}(x,y)$ and $h_{44}(x,y)$ decay to zero at the spatial infinity.

Now let us examine gravity on the brane. The fluctuations of the metric on the brane have the following form

$$h_{\mu\nu}(x,0) = b_{\mu\nu}(x,0) + \frac{\hat\kappa k}{6}\,\eta_{\mu\nu}\Box^{-1}t. \tag{41}$$

Using (38), one can easy see that equation (41) coincides with the solutions for gravity on the brane, obtained in [6, 7, 8, 5], although we did not use the "bent-brane" formulation, which was used in [6, 7].

Finally, we have to answer the question, which was posed in the title of the paper. Obviously, it amounts to finding the number of the independent degrees of freedom in the RS2 model. As we have shown, we cannot completely gauge away the radion field in the presence of matter on the brane (see (19)). The situation is rather different, if there is no matter on the brane. In this case we deal with equations for the free fields, possessing solutions of the plane wave type, which do not vanish at infinity. Therefore, we have to drop the physical boundary conditions for all the components of the metric fluctuations. Thus, there is no need for the gauge function ξ_4 to decay to zero at $y \to \pm\infty$ (though the functions ξ_μ must still decay to zero at $y \to \pm\infty$, because ξ^M must be finite everywhere in E and $\xi_\mu = e^{2\sigma}\eta_{\mu\nu}\xi^\nu$). It means that the radion field can be gauged out and is no more an independent degree of freedom of the RS2 model in this case. Nevertheless, the radion field appears, if we place matter sources on the brane, and it allows us to solve consistently the equations of motion.

We can find an analogy to this situation in electrodynamics. It is a common knowledge that longitudinal photons do not appear in the asymptotic states (on the mass shell), whereas their contribution is important in the radiative corrections (off the mass shell). The radion field is very similar to longitudinal photons: it is absent in the asymptotic states, but it is absolutely necessary for consistently describing the interaction off the mass shell.

There is another problem, which may arise in the case of the absence of matter on the brane. Since we drop the physical boundary conditions for the field A_μ ($A_\mu|_{y\to\pm\infty} \to 0$), the gauge parameter ξ_μ, defined by formula (24), may not decay to zero $\sim e^{2\sigma}$ at infinity. This means that there may be additional degrees of freedom in the RS2 model. This problem deserves a more detailed investigation.

4 Conclusion

In the present paper we have studied the boundary conditions for the metric fluctuations and the gauge functions in the RS2 model with and without matter on the branes and solved exactly the equations of motion in the presence of matter on the brane in a convenient gauge. The validity of the imposed gauge conditions was carefully checked. The gauge is very simple and is more transparent from the physical point of view, than the gauge used in [8], where the equations for linearized gravity were solved exactly as well. Another advantage of this gauge choice is that the brane remains straight in this case. We have shown that although the radion is not an independent degree of freedom of the model, it is indispensable in the case of the presence of matter on the brane (in this case the radion field cannot be completely gauged away). The analysis made above is completely equivalent to the one made in [3, 4], where linearized gravity in the RS1 model was treated. We believe that the physically transparent method, which was used in this paper, is useful for understanding the general structure of both Randall-Sundrum models.

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