

## Towards detecting gravitational waves: A contribution by Richard Feynman

M. Di Mauro

*Dipartimento di Matematica, Università di Salerno,  
Fisciano, 84084, Italy  
E-mail: madimauro@unisa.it*

S. Esposito\* and A. Naddeo†

*INFN, Sezione di Napoli, C. U. Monte S. Angelo, Via Cinthia,  
Napoli, 80125, Italy*

*\*E-mail: sesposit@na.infn.it*

*†E-mail: anaddeo@na.infn.it*

An account of Richard Feynman's work on gravitational waves is given. Feynman's involvement with this subject can be traced back to 1957, when he attended the famous Chapel Hill conference on the Role of Gravitation in Physics. At that conference, he presented in particular the celebrated sticky bead argument, which was devised to intuitively argue that gravitational waves must carry energy, if they exist at all. While giving a simple argument in favor of the existence of gravitational waves, Feynman's thought experiment paved the way for their detection and stimulated subsequent efforts in building a practical detecting device. Feynman's contributions were systematically developed in a letter to Victor Weisskopf, completed in February 1961, as well as in his Caltech Lectures on Gravitation, delivered in 1962-63. There, a detailed calculation of the power radiated as gravitational radiation was performed, using both classical and quantum field theoretical tools, leading to a derivation of the quadrupole formula and its application to gravitational radiation by a binary star system. A comparison between the attitudes of Feynman and of the general relativity community to the problems of gravitational wave physics is drawn as well.

*Keywords:* History of physics; History of relativity; Gravitational waves.

### 1. Introduction

The contributions of Richard P. Feynman to physics notoriously touched all four fundamental interactions of Nature. His first breakthrough occurred in the theory of electromagnetism, with his version of covariant quantum electrodynamics that earned him the 1965 Nobel prize,<sup>1</sup> which was developed by him between the late 1940s and the early 1950s. A few years later, Feynman's interest had focused on another fundamental interaction, namely gravity. Feynman first mentioned this new interest of his to Murray Gell-Mann, who much later recalled:

We first discussed it when I visited Caltech during the Christmas vacation of 1954-55 [...] I found that he had made considerable progress.<sup>2</sup>

In view of this statement,<sup>a</sup> it is conceivable that Feynman's interests were directed towards gravity some time before 1954, probably shortly after completing his work on quantum electrodynamics. While working also on other subjects, most notably condensed matter physics and the theory of weak interactions,<sup>5</sup> Feynman nurtured his interest in gravity at least until the second half of the 1960s. In these fifteen years, he gave several contributions to the both classical and quantum gravity, some of which would later be recognized as pivotal for the field. The first public contribution to gravity was given by Feynman at the Chapel Hill conference in 1957,<sup>4</sup> where he took active part to many of the numerous discussion sessions. After that, records of his later work are documented by several published and unpublished sources. For detailed historical accounts of Feynman's contributions to gravitational physics, see Refs. 6 and 8.

In this paper, we focus on Feynman's work on gravitational waves. As well-known, at Chapel Hill Feynman proposed a simple and intuitive thought experiment in favor of the existence of gravitational waves. This "sticky bead" argument presumably contributed to inspiring the pioneering experimental efforts by Joseph Weber. In fact, Feynman's qualitative argument was supported and extended by detailed calculations, several results of which were presented at Chapel Hill as well. While the original calculations are presumably lost, Feynman included a detailed description of an updated version of them in a letter he wrote to Viktor F. Weisskopf in early 1961.<sup>9</sup> These updated computations were also included in the famous graduate lectures on gravitation he delivered at Caltech in the academic year 1962-63.<sup>7</sup> They show that Feynman had addressed most of the contemporary theoretical problems of the subject, showing that gravitational waves carry energy, and that they can be detected by suitable instruments; moreover, he computed in detail the energy radiated by binary self-gravitating systems. Feynman's comments clearly show that he regarded his results as compelling (and probably somewhat straightforward as well, since he did not publish them) solutions to the above mentioned issues. Indeed, in his subsequent work on gravity, Feynman did not deal with gravitational waves any more, focusing instead on quantum gravity.

The paper is organized as follows. In Sect. 2 we briefly sketch the history of gravitational waves prior to Feynman's engagement with them, highlighting the theoretical problems which were the concern of scientists in the 1950s and 1960s. In Sect. 3 we briefly introduce the historical context in which the Chapel Hill conference took place and we summarize Feynman's contributions to it. In Sect. 4 we examine the letter to Weisskopf, and the parts of the Lectures on Gravitation which discuss gravitational waves. We close this section with a summary of Feynman's solutions to the theoretical issues in gravitational wave research. In Sect. 5 we give some comments on Feynman's work on gravitational waves, in particular in connection with his general views on gravity and on fundamental interactions in general.

---

<sup>a</sup>This was confirmed by Bryce S. DeWitt, who declared: "Even by 1955 Feynman claimed to have spent a great deal of effort on the problem of gravitation".<sup>3</sup>

In Sect. 6 we outline some contemporary and later developments, and in particular we describe the solutions to the theoretical issues that are currently accepted by the scientific community. Sect. 7 is devoted to conclusions.

## 2. Brief history of gravitational waves up to the 1950s

The main open problem concerning gravitational waves, when Feynman tackled them, was their very existence as physical entities.<sup>b</sup> In fact, general relativity enjoys general covariance, which means that coordinate systems have no intrinsic meaning. While very elegant and powerful, this symmetry also poses great difficulties, which have kept haunting general relativity practitioners since the earliest days of the theory. Namely, it is not easy to distinguish between real physical phenomena and mere artifacts due to a bad coordinate choice, hence invariant characterizations are needed. One of the earliest examples is the Schwarzschild singularity,<sup>11</sup> which occurs in the spherically symmetric solution found by Karl Schwarzschild. In fact, the metric describing this solution in spherical coordinates displays a singularity on a surface located at a given value of the radial coordinate. This singularity is now well-known to be apparent, and it is removed by choosing a different coordinate system,<sup>12</sup> but it took more than forty years to really understand what this meant. Two other, strictly linked examples, are given by the definition of energy in general relativity, and by gravitational waves themselves. When Albert Einstein first showed in 1916<sup>13</sup> that the gravitational field equations he had written down the year before<sup>14</sup> predict in the weak field limit the existence of wave-like excitations, and when in 1918<sup>15</sup> he corrected a major mistake in his 1916 paper, finding his celebrated quadrupole formula describing the leading-order energy emission through gravitational radiation, he chose a particular coordinate system, in which his equations looked formally analogous to the equations of electromagnetism. Einstein immediately recognized that some of the wave solutions he had found were spurious, and could be eliminated by a coordinate change (they were flat space in curved coordinates), while the remaining ones were not spurious, and carried energy according to his formula.

### 2.1. *The question of the existence of gravitational waves*

A weak point in Einstein's derivation was spotted and corrected by Sir Arthur S. Eddington,<sup>16</sup> namely, the fact that Einstein's choice of coordinates explicitly contained the speed of light, hence the propagation speed of gravitational waves may have been inadvertently put in by hand by the German physicist. Eddington improved and extended Einstein's work, giving a more rigorous proof of the fact that some of Einstein's solution were not coordinate artifacts, they carried energy and they propagated with the speed of light. Finally, Eddington rederived the

---

<sup>b</sup>For details on the history of gravitational waves, with a focus on the theoretical side, we refer to Ref. 10.

quadrupole formula, correcting a minor error by Einstein (an overall factor of 2), and applied it to the computation of energy radiated away by a rigid rotator. However, in complaining about the lack of an invariant way of distinguishing physical from spurious waves, Eddington referred to the latter in a very suggestive way, stating that, being coordinate artifacts, they propagate with the “speed of thought” (Ref. 17, p. 130). This generated a misunderstanding according to which Eddington attributed this characteristic to gravitational waves in general, thus questioning their very existence. Indeed, doubts concerning the existence of gravitational waves did not stop bothering the scientists working in general relativity for a long time. Another problem was posed by the fact that, unlike electromagnetism, gravitation is described by a highly nonlinear theory, while gravitational waves had been found only in the linearized approximation. The possibility thus existed that gravitational waves were in fact only artifacts of the linearized theory, meaning that there is no solution to the full gravitational field equations describing gravitational fields propagating as waves. This point of view was shared for some time by Einstein himself, after in 1937 he had tried with Nathan Rosen to find plane wave solutions to the full gravitational field equations.<sup>18</sup> Indeed, the two physicists found singularities in their solutions, and interpreted them as obstructions to the existence of propagating solutions to the equations.<sup>c</sup> After a well-known incident with a referee,<sup>20</sup> Einstein finally realized that the singularities he had found were coordinate artifacts, and that in fact he and Rosen had found an exact solution to his field equation, which enjoyed cylindrical symmetry. This was one of the first solutions to the full theory describing gravitational waves.<sup>d</sup> However, the question of the physical effects ascribable to these waves was still unclear, since it seemed that they did not carry energy, as still argued by Rosen himself in 1955 (Ref. 22, pp. 171-174), and anyway the Einstein-Rosen solution was non-physical, since its source was not localized. What was needed was an exact solution describing waves radiating from a localized center, which was still unavailable at the time. In any case, the fact that even Einstein himself had doubted that gravitational waves could exist certainly contributed to making them a neglected field of study for twenty more years.

A very important breakthrough occurred in 1956, when Felix A. E. Pirani managed to give an invariant characterization of gravitational radiation, in terms of spacetime curvature rather than energy,<sup>23,24</sup> giving in fact birth to the modern popular description of gravitational waves as propagating ripples of curvature. This work was performed in the context of Pirani’s investigations of the physical meaning of the Riemann curvature tensor, based on the geodesic deviation equation<sup>25</sup> and on the classification of curvature tensors in terms of their principal null directions.<sup>26</sup> In particular, using the geodesic deviation equation, Pirani showed that the passage of a gravitational wave should modify the proper distance between test particles,

<sup>c</sup>Einstein mentioned this in a letter to Max Born (Ref. 19, letter 71).

<sup>d</sup>Actually, Einstein and Rosen had rediscovered a solution first found by Guido Beck in 1925.<sup>21</sup>

as an effect of the variation of the curvature. Thus, a measurable effect could be ascribed at least in principle to gravitational waves.

## 2.2. *The question of energy loss*

The issue of existence was not the only one which was at stake in gravitational wave physics in the 1950s. Even taking existence for granted, indeed, there was a problem concerning gravitational radiation by self-gravitating systems, such as binary stars. The first applications by Einstein and Eddington involved rigid bodies such as rotators, which can be considered to be kept together by the electromagnetic interaction, while a bound state kept together by gravity itself is beyond the reach of the linearized approximation, which was the only context in which gravitational energy radiation had been studied. In fact, many physicists even doubted that gravitational waves were radiated at all by such a system. And even if radiation did occur, it was unclear whether the Einstein quadrupole formula, which had been obtained in the linearized theory, correctly described the resulting energy loss. The issue had been addressed for the first time in 1941 by Lev D. Landau and Evgenij M. Lifshitz, in the first edition of their textbook,<sup>27</sup> where the binary system was treated by using the post-Newtonian approximation, and energy loss was computed by applying the quadrupole formula. However, there was no consensus about the correctness of their calculation, and the question was still open in the 1950s.

## 2.3. *Summary of the open problems*

From what we said above, it emerges that the situation concerning gravitational wave research was far from clear in the 1950s, with many basic theoretical problems and no hope of experimental guidance. We may summarize the main issues at stake as follows:

- (1) The actual existence of gravitational waves as physical entities, their speed of propagation and their energy conveying;
- (2) The existence of gravitational waves as solutions to the full nonlinear gravitational field equations;
- (3) The radiation of gravitational waves by self-gravitating systems and the correctness of the quadrupole formula in describing the energy loss.

## 3. **The Chapel Hill conference**

As we saw, before the 1950s research on gravitational waves was carried out by only a handful of pioneers. This lack of interest was in fact not only the result of the doubts expressed by Einstein and also attributed to Eddington. The whole field of general relativity remained dormant for thirty years, from the mid-1920s to the mid-1950s, after an initial burst of activity. During this period, later baptized “low-watermark” phase,<sup>28–30</sup> general relativity was considered by most physicists to be

a rather esoteric and heavily mathematical subject, with tenuous relations with the physical world.

Around the mid-1950's, things began to change, and gravity slowly regained a prominent place in physics. Pivotal to this change of attitude, which was dubbed the “renaissance” of general relativity,<sup>31–33</sup> was the organization of a series of international conferences entirely devoted to the subject. The renaissance of general relativity was characterized by the fact that physicists began studying the theory in a less speculative fashion than before, by focusing on its physical implications, and by developing dedicated, i.e. intrinsically general relativistic methods. That was also a time where researchers from other fields, most notably particle and field theory, began to be interested on gravitation and to apply their methods to it. One of them was of course Feynman, who started working on gravity just in this period, and it was in one of these conferences, namely the one (organized by DeWitt and his wife Cécile DeWitt-Morette) at the University of North Carolina at Chapel Hill in January 1957,<sup>4</sup> that he first announced his results in the field, as we anticipated in the introduction. In his many contributions to the discussions at Chapel Hill, he clearly delineated his attitude towards gravity, and presented a host of results he had already obtained. Besides the arguments on favor of the existence of gravitational waves, which we discuss in the following subsections, Feynman sketched a proposal for a field-theoretical approach to classical gravity. His view, shared by other particle physicists, was indeed that gravity had to be regarded as a fundamental interaction like all the others, and hence it had to be described by a field theory, which would also encode quantum corrections to the classical theory. Indeed, within a few years, he managed to derive the field equations of general relativity (as summarized in Ref. 7), and he attacked the problem of quantum gravity, from this perspective.<sup>6,8</sup> Finally, the Chapel Hill conference is notably one of the few occasions where Feynman expressed his views about foundational quantum issues, which were inspired by the problem of the quantization of gravity.<sup>4,6,8,34</sup>

### 3.1. *The sticky bead argument*

Feynman presented his famous sticky bead argument in a session devoted to discussing the necessity of gravity quantization (in which he also proposed a thought experiment in order to argue in favor of that). In fact, Feynman had arrived a day later at the conference<sup>e</sup>, skipping the session devoted to gravitational waves. However, further discussion of gravitational waves in sessions devoted to quantum gravity was not off-topic, since the existence of these waves is of course very important for the quantization of the theory. Thus, in the middle of a discussion about whether the gravitational field had to be quantized even in the absence of gravitational waves, Feynman proposed a simple physical argument in favor of their existence (Ref. 4, p. 260 and pp. 279–281). He argued that if gravitational waves

<sup>e</sup>An amusing and well-known recollection of his arrival in North Carolina can be found in Ref. 35.

exist, they must carry energy and this, together with the existence of these waves as solutions of the linearized theory, was enough for him to be confident in their existence. He expressed this intuitive feeling with the words: “My instincts are that if you can feel it, you can make it” (Ref. 4, p. 260). Feynman’s reasoning was detailed in an expanded version of his remarks, included in the records of the conference<sup>4</sup>:

I think it is easy to see that if gravitational waves can be created they can carry energy and do work. Suppose we have a transverse-transverse wave generated by impinging on two masses close together. Let one mass  $A$  carry a stick which runs past touching the other  $B$ . I think I can show that the second in accelerating up and down will rub the stick, and therefore by friction make heat. I use coordinates physically natural to  $A$ , that is so at  $A$  there is flat space and no field [...]. Then Pirani at an earlier section gave an equation for the motion of a nearby particle. (Ref. 4, p. 279).

The result by Pirani is of course that obtained in Refs. 23 and 24 (which indeed had been presented earlier at the conference, cf. Ref. 4, p. 141), stating that the displacement  $\eta$  of the mass  $B$  (measured from the origin  $A$  of the coordinate system) in the field of a gravitational wave satisfies the following differential equation:<sup>f</sup>

$$\ddot{\eta}^a + R_{0b0}^a \eta^b = 0, \quad (a, b = 1, 2, 3) \quad (1)$$

$R$  being the Riemann curvature tensor at the point  $A$ . Feynman continued:

the curvature tensor [...] does not vanish for the transverse-transverse gravity wave but oscillates as the wave goes by. So,  $\eta$  on the RHS is sensibly constant, so the equation says the particle vibrates up and down a little (with amplitude proportional to how far it is from  $A$  on the average, and to the wave amplitude.) Hence it rubs the stick, and generates heat. (Ref. 4, p. 279)

The upshot is that the stick absorbs energy from the gravitational wave, which means that the latter carries energy and is able to do work.

### 3.2. Feynman’s theoretical detector

In connection with the device he considered, Feynman went on considering a possible gravitational wave detector in which there are four, rather than two test masses, which oscillate as shown in Figure 1.

This thought device was used to compute how much energy gravitational waves would carry. The device was described by Feynman as follows:

If I use 4 weights in a cross, the motions at a given phase are as in the figure (Fig. 1). Thus a quadrupole moment is generated by the wave. Now the

<sup>f</sup>This follows from the geodesic deviation equation (Ref. 4, p. 141; Refs. 23 and 24).

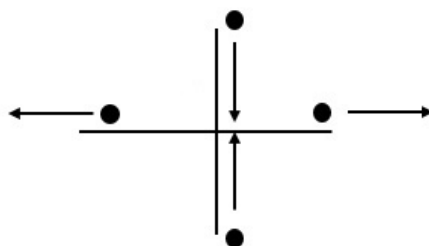


Fig. 1. Scheme of Feynman's gravitational wave detector.

question is whether such a wave can be generated in the first place. First since it is a solution of the equations (approx.) it can probably be made. Second, when I tried to analyze from the field equations just what happens if we drive 4 masses in a quadrupole motion of masses like the figure above would do - even including the stress-energy tensor of the machinery which drives the weights, it was very hard to see how one could avoid having a quadrupole source and generate waves. Third my instinct is that a device which could draw energy out of a wave acting on it, must if driven in the corresponding motion be able to create waves of the same kind. [...] If a wave impinges on our "absorber" and generates energy - another "absorber" placed in the wave behind the first must absorb less because of the presence of the first, (otherwise by using enough absorbers we could draw unlimited energy from the waves). That is, if energy is absorbed the wave must get weaker. How is this accomplished? Ordinarily through interference. To absorb, the absorber parts must move, and *in moving generate a wave* which interferes with the original wave in the so-called forward scattering direction, thus reducing the intensity for a subsequent absorber. In view therefore of the detailed analysis showing that gravity waves can generate heat (and therefore carry energy proportional to  $R^2$  with a coefficient which can be determined from the forward scattering argument). I conclude also that these waves can be generated and are in every respect real. (Ref. 4, p. 280, emphasis in the original)

In this quote, Feynman's point of view about the existence of gravitational waves is evident: since they exist as solutions of the field equations (albeit in the linearized approximation), they carry energy, and they can be generated (in fact, the detector generates secondary waves), then they must be a real phenomenon.

### 3.3. Binary systems

Within the discussion (Ref. 4, p. 260), Feynman also quoted a result concerning the calculation of the energy radiated by a self-gravitating two-body system in a circular orbit. This result shows that he had addressed also this issue, performing

detailed calculations. The quoted result is:

$$\frac{\text{Energy radiated in one revolution}}{\text{Kinetic energy content}} = \frac{16\pi}{15} \frac{\sqrt{mM}}{m+M} \left(\frac{u}{c}\right)^5, \quad (2)$$

where  $m$  and  $M$  are the masses of the two bodies, and  $u$  is their relative velocity. In the case of the Earth-Sun system, this formula describes as expected a tiny effect, leading to a huge order of magnitude (about  $10^{26}$  years) for the lifetime of the motion of the Earth around the Sun. Despite the smallness of the effect, this is a definite prediction. Feynman stated to have performed a full analysis of this problem some time before (Ref. 4, p. 280), but he only quoted the result, without presenting his computations. Fortunately, Feynman reported a version of them four years later, in the letter written to Victor F. Weisskopf,<sup>9</sup> to which we now turn.

#### 4. The letter to Weisskopf and the sixteenth lecture on gravitation

As anticipated, a complete and systematic description of Feynman's computations on gravitational waves can be found in a letter he wrote to Weisskopf in February 1961,<sup>9</sup> to answer a question that the Austrian physicist had asked him in the fall of 1960, concerning the reality of gravitational radiation. The letter was so detailed that it was subsequently included in the material distributed to the students attending the Caltech lectures in 1962-63. Indeed, the sixteenth lecture of that course (the last one in the published version<sup>7</sup>) dealt with gravitational waves, and reproduced part of the computations showed in the letter itself, with additional interesting comments.

The computations that Feynman reported in the letter and in the lectures were surely related to those he had performed before the Chapel Hill conference, but included several improvements that Feynman had conceived meanwhile. Indeed, at the end of the letter, he recalled the conference, claiming that

It was this entire argument used in reverse that I made at a conference in North Carolina several years ago to convince people that gravity waves must carry energy. [...] Only as I was writing this letter to you did I find this simpler argument from the Lagrangian (Ref. 9, p. 14).

What Feynman meant by "argument used in reverse" and by "simpler argument from the Lagrangian" will be clear by the end of this section.

The most striking fact about the computations is that they are performed adopting a quantum point of view, treating general relativity as a quantum field theory, and then considering the classical limit:

My view is quantum mechanical, but the classical limits are easily derived. (Ref. 9, p. 6)

Only later the same computation is repeated from the usual, classical point of view, in the framework of linearized gravity. As we saw, in fact, in that period Feynman

was struggling with the quantization of gravity, building on the field theoretical viewpoint that he had advocated at Chapel Hill. In the beginning of 1961, he had recognized that loop diagrams in the theory present major difficulties, but he was still far from a solution (later in the same year he would report on his progress at the La Jolla conference<sup>36</sup>). However, he could safely study classical gravity by applying his field theoretical methods to tree diagrams, which are the only ones relevant to the classical limit (while loop diagrams describe quantum corrections). This is what he did in the letter,<sup>g</sup> claiming that:

I am studying the problem of quantization of Einstein's General Relativity. I am still working out the details of handling the divergent integrals which arise in problems in which some virtual momentum must be integrated over. But for cases of radiation, without the radiation corrections, there is no difficulty. (Ref. 9, p. 1)

The "radiation corrections" Feynman was referring to are of course what are usually called radiative corrections, i.e. higher order corrections to the processes, which include the troublesome loop diagrams. In fact, in the Lectures Feynman adopted this point of view in studying many other problems in classical gravity:

All other problems in the theory of gravitation<sup>h</sup> we shall attack first by the quantum theory; in order to obtain the classical consequences on macroscopic objects we shall take the classical limits of our quantum answers. (Ref. 7, p. 163)

The field theoretical methods that Feynman used are intrinsically perturbative. Feynman explicitly discussed the validity of this approximation, and of the linearized approximation he used in the classical computation, stating that this is a natural and obvious choice in view of the extreme weakness of the gravitational interaction. He stated in fact that:

I won't be concerned with fields of arbitrary strength [...]. I am surprised that I find people objecting to an expansion of this kind, because it would be hard to find a situation where numerically a perturbation series is more justified! (Ref. 9, p. 1)

which is confirmed in the Lectures:

There needs to be no apology for the use of perturbations, since gravity is far weaker than other fields for which perturbation theory seems to make extremely accurate predictions. (Ref. 7, p. 207)

---

<sup>g</sup>A conceptually analogous calculation was performed in 1936 by Matvei Bronstein,<sup>37</sup> who derived the quadrupole formula with the correct factor of 2 by computing the emission coefficients of transverse gravitons.

<sup>h</sup>Here Feynman was referring to all problems, apart from that of a spherical mass distribution and cosmology.

From these quotations, it is evident that Feynman considered the contemporary debate around the existence of gravitational waves in the full nonlinear theory of general relativity, as opposed to the linearized theory, to be pointless, since the perturbative/linearized theory would furnish an excellent approximation in most cases of interest.<sup>i</sup>

#### 4.1. *The quantum computation*

To perform his computation, Feynman started from linearized gravity, which from his point of view was the linear theory of a massless charged spin-2 quantum field coupled to matter. For simplicity, he considered scalar (spin-0) matter, and he computed the probabilities for single graviton emission in several processes involving matter particles, in the low energy limit. The result is that the probability of emission of a graviton with frequency  $\omega$  in the solid angle  $d\Omega$  is (Ref. 9, p. 7; Ref. 7, p. 214):

$$P = a^2 \frac{d\Omega}{4\pi} \frac{d\omega}{\omega} \frac{\lambda^2}{4\pi^2}, \quad (3)$$

where  $a$  is a kinematical factor and  $\lambda$  is the gravitational coupling constant (which is proportional to the square root of Newton's constant  $G$ ).

Feynman knew that the probabilities of radiation of massless quanta become universal in the low energy limit, i.e. the probability of emission of a soft quantum in an interaction is independent of the spin of the interacting quanta (hence the choice of scalar matter implies no loss of generality), and most importantly of the kind of interaction which is involved. This happens because the low-energy limit is equivalent to the long-wavelength limit, in which the physics is insensitive to short-distance details. In particular, soft graviton emission occurs, with the same probability, also when matter quanta interact gravitationally. Since classical radiation is related to soft quantum emission, the implication is that masses accelerating under the reciprocal gravitational interactions must emit gravitational radiation as any other accelerating mass:

Although this was worked out for spin zero particles, the result, as  $\omega \rightarrow 0$ , is the same for all, spin 1/2, photons, etc. It is correct for collisions irrespective of the kind of force. For example, Schiff asked me if two masses under their mutual gravitation can radiate. The answer is certainly yes. (Ref. 9, p. 7)

According to Feynman, these results proved that self-gravitating system must radiate gravitational waves. This view was confirmed in the Lectures:

---

<sup>i</sup>He also acknowledged the fact that the problem was at the moment of purely academic interest, stating that "the most "practical" thing to do is to go to zero order and forget the whole problem altogether" (Ref. 9, p. 1).

As far as the radiation is concerned, the exact nature of the over-all scattering process is not important. I emphasize the last point because there are always some theorists who go about mumbling some mystical reasons to claim that the radiation would not occur if the scattering is gravitational - there is no basis for these claims; as far as we are concerned, radiation of gravity waves is as real as can be; the sun-earth rotation must be a source of gravitational waves. (Ref. 7, p. 215).

Thus the issue of gravitational radiation by self-gravitating systems was considered solved by Feynman. We emphasize that his quantum point of view was pivotal to that conclusion, since his reasoning relied on a well-known result of quantum field theory, namely the universality of soft graviton emission. Once again, Feynman showed some annoyance towards the physicists who continued to have doubts, while the solution was so clear to him.

#### 4.2. *The classical computation and the quadrupole formula*

In the second part of the letter, Feynman switched to a classical computation, which was considered to be more appropriate for macroscopic objects, such as celestial bodies:

for the motion of big objects such as planets and stars it may be more consistent to work in the classical limit. (Ref. 7, p. 215)

The classical computation was developed in close analogy with electrodynamics, taking into account that in the case of gravitation the source is a tensor  $S_{\mu\nu}$  rather than a vector  $J_\mu$ . The differential equation which has to be solved to find classical gravitational waves is (in the notation of Ref. 7):

$$\square^2 \bar{h}_{\mu\nu} = \lambda S_{\mu\nu}, \quad (4)$$

where  $h_{\mu\nu}$  is the field describing deviations of the metric from the flat Minkowski metric and the bar operation is defined as:

$$\bar{h}_{\mu\nu} = \frac{1}{2} (h_{\mu\nu} + h_{\nu\mu}) - \frac{1}{2} \eta_{\mu\nu} h^\sigma{}_\sigma. \quad (5)$$

$\square^2$  is the usual, flat-space, d'Alembertian operator. As well-known, the above equation corresponds to the linearized Einstein equations in the de Donder gauge  $\partial^\mu \bar{h}_{\mu\nu} = 0$ . When all quantities are periodic with a given frequency  $\omega$ , the solution at a point 1 located at a distance from the source much greater than the linear dimensions of the source itself (which is the region where  $S_{\mu\nu}$  is expected to be large):

$$\bar{h}_{\mu\nu}(\vec{r}_1) = -\frac{\lambda}{4\pi r_1} e^{i\omega r_1} \int d^3\vec{r}_2 S_{\mu\nu}(\vec{r}_2) e^{-i\vec{K}\cdot\vec{r}_2}, \quad (6)$$

with  $|\vec{r}_1| \gg |\vec{r}_2|$  as stated. This approximation holds for nearly all cases of astronomical interests, where wavelengths are much longer than the system's dimensions,

such as for instance binary stars and the Earth-Sun system. Finally, Feynman assumed that the motions of matter in the source were slow, so that he could resort to the post-Newtonian approximation. This is where the computations in the last section of Lecture 16 of the Caltech Lectures (Ref. 7, pp. 218-220) stopped, while in the letter Feynman went on computing the power radiated by the above waves in the quadrupole approximation which, for a periodic motion of frequency  $\omega$ , read (Ref. 9, p. 11):

$$\frac{\text{mean energy radiated}}{\text{sec.}} = \frac{1}{5} G \omega^6 \sum_{ij} |Q'_{ij}|^2, \quad (7)$$

where  $Q'_{ij} = Q_{ij} - \frac{1}{3} \delta_{ij} Q_{kk}$ ,  $Q_{ij} = \sum_a m_a R_i^a R_j^a$  is the quadrupole mass moment, and the root mean square average is taken. The result (7) was then shown to agree with the quantum mechanical probability (3) computed in the first part of the letter (after suitable averaging). To strengthen this result, Feynman had considered earlier (Ref. 9, p. 10) an analogous comparison for the case of electromagnetism, finding again perfect correspondence.

Feynman then applied his formulas to the case of a circularly rotating double star (Ref. 9, p. 12), promptly recovering the result (2). In sum, Feynman's classical computation was analogous to that performed earlier by Landau and Lifshitz. However, his treatment was simpler, since he managed by using a very ingenious method for computing the energy density, which essentially exploits the fact that for classical transverse plane waves the linearized gravity Lagrangian reduces to that of the harmonic oscillator. This spared him formal complications such as the cumbersome energy-momentum pseudo-tensor, which was used by Landau and Lifshitz. This is in fact the "simpler argument from the Lagrangian" which he referred to in the end of the letter.

The above treatment was then supplemented with a thorough analysis of the effects of a gravitational wave impinging on a device made of two test particles placed on a rod with friction, in this way providing a more complete description of the working principle of the gravitational wave detector previously introduced at Chapel Hill. A second absorber, made of four moving particles in a quadrupole configuration, as in Figure 1, was also considered, and shown to be able to absorb energy from a gravitational wave acting on it. The oscillating device was shown to re-radiate waves with the same energy content. Apparently, at Chapel Hill, Feynman had derived the expression for the radiated energy (which was then applied to the binary system case) from the detailed study of the quadrupolar detector, either because at that time he did not know how to extract the definition of energy from the gravitational Lagrangian, or because the existing methods were considered to be too cumbersome by him. In the letter, instead, Feynman found a simple way of taking the opposite route (from this we can understand why Feynman claimed that the argument at Chapel Hill had been "used in reverse"), since the quadrupole formula was derived in general from the linearized Einstein equations and then applied to the detector case.

Thus, Feynman had shown that gravitational waves carry energy, and he had computed how much, also in the case of a binary star, satisfactorily addressing both the first and the third of the above issues. At the end of Lecture 16 of Ref. 7, Feynman commented again on the energy content of gravitational waves:

What is the power radiated by such a wave? There are a great many people who worry needlessly at this question, because of a perennial prejudice that gravitation is somehow mysterious and different - they feel that it might be that gravity waves carry no energy at all. We can definitely show that they can indeed heat up a wall, so there is no question as to their energy content. The situation is exactly analogous to electrodynamics (Ref. 7, p. 219).

and in the letter, while recalling the Chapel Hill conference he commented:

I was surprised to find a whole day at the conference devoted to this question, and that “experts” were confused. That is what comes from looking for conserved energy tensors, etc. instead of asking “can the waves do work?” (Ref. 9, p. 14).

These two quotes again display Feynman’s annoyance towards the relativity community. The fact that relativists kept arguing about these problems without reaching an agreement, and that they privileged sophisticated formal tools to plain physical thinking, definitely disturbed Feynman, who repeatedly expressed his annoyance, and may have contributed to his loss of interest in the subject.

#### **4.3. Feynman’s answer to the three issues**

The detailed study of Feynman’s work on gravitational waves reveals what he thought the solutions to the issues listed in Sect. 2 should be, at least from a theoretical point of view, pending the ultimate experimental verification. In summary, these were:

- (1) Feynman’s thought experiments and calculations clearly show that gravitational waves exist and that they carry energy, while the fact that they propagate with the speed of light is a consequence of the fact that they emerged from massless quanta, i.e. the gravitons;
- (2) Since gravity is so weak, it makes perfect sense to study gravitational waves using the linearized approximation;
- (3) Gravitationally-bound system emit gravitational radiation as any other bound system, and the energy loss is described by the quadrupole formula in the approximations valid in most situations of interest.

## 5. Comments on Feynman's attitude towards gravity and gravitational waves

As emphasized, Feynman's approach to gravitational waves, and to gravitation in general, was much closer in spirit to particle physics than to general relativity. In fact, Feynman preferred a field theoretical approach over the geometrical one which had become the standard one among relativists. In his opinion, indeed, the latter approach divided gravity from other fundamental interactions, preventing the investigation of the relation of gravitation with the rest of physics, and also posing great obstacles towards its quantization.

A second motivation which underlies Feynman's choice of using quantum field theoretical methods for investigating classical gravitational radiation and other problems in classical gravity, was his belief that quantum mechanics underlies Nature at the most fundamental level, with the forces we observe at the macroscopic level emerging from quantum interactions in the classical limit. This is most clearly expressed by him in some unpublished lectures:

I shall call conservative forces, those forces which can be deduced from quantum mechanics in the classical limit. As you know, Q.M. is the underpinning of Nature... (Ref. 38, p. 35)

Feynman recognized that the main problem with gravity was the fact that general relativity had received only a handful of experimental confirmations, while the subjects of gravitational waves and quantum gravity were confined to pure theory. These subjects were being investigated by the relativity community by resorting to sophisticated mathematics, in the hope that rigor could be a substitute for empirical evidence. Feynman had a different point of view. To him, the best way to proceed was to try to extract physical predictions from the theory *as if* these were easily accessible experimentally. This viewpoint was strongly advocated by him at Chapel Hill in some critical comments:

There exists, however, one serious difficulty, and that is the lack of experiments. [...] so we have to take a viewpoint of how to deal with problems where no experiments are available. There are two choices. The first choice is that of mathematical rigor. [...] The attempt at mathematical rigorous solutions without guiding experiments is exactly the reason the subject is difficult, not the equations. The second choice of action is to "play games" by intuition and drive on. Take the case of gravitational radiation. [...] I think the best viewpoint is to pretend that there are experiments and calculate. In this field since we are not pushed by experiments we must be pulled by imagination. (Ref. 4, pp. 271-2)

and shortly after

The real challenge is not to find an elegant formalism, but to solve a series of problems whose results could be checked. This is a different point of view. Don't be so rigorous or you will not succeed. (Ref. 4, p. 272)

This is in fact the viewpoint that Feynman adopted in his investigations of gravitational waves, but also in his work on quantum gravity.<sup>8</sup>

## 6. Contemporary and subsequent developments

When the Chapel Hill conference took place, the time was ripe for the existence of gravitational waves to be accepted by most physicists. Thus, the work of Pirani, and Feynman's sticky bead argument, managed to convince people that gravitational waves belong to the realm of physical phenomena, and suggested ways to investigate their physical effects. In fact, an argument similar to Feynman's was conceived independently by a leading relativist, Hermann Bondi, who was also present at Chapel Hill. This is referred to by several of Bondi's remarks at the conference, such as the following one, made after Pirani's talk (Ref. 4, p. 142): "Can one construct in this way an absorber for gravitational energy by inserting a  $d\eta/d\tau$  term, to learn what part of the Riemann tensor would be the energy producing one, because it is that part that we want to isolate to study gravitational waves?". The absorber of gravitational energy is just a more formal description of the "stickiness" of Feynman's sticky-bead. Shortly after the conference, Bondi published his variant of the sticky-bead device,<sup>39</sup> although unlike Feynman he did not succeed in relating the intensity of the gravitational wave to the amount of energy carried by it. Inspired by these discussions, another participant to the conference, Joseph Weber, soon undertook his lifetime effort to experimentally detect gravitational waves<sup>40</sup>; Weber built his famous resonant bar detector in 1966<sup>41</sup> and even announced the first experimental detection of gravitational waves coming from the center of the Milky Way in 1969.<sup>42</sup> While this finding was later disproved, Weber's works triggered all the subsequent research on the detection of gravitational waves, which culminated in the monumental detections by the LIGO-Virgo collaboration in 2016.<sup>43</sup> Among all the physical results that this brought about, the confirmation came that gravitational waves move with the speed of light.<sup>44</sup>

Thus, it may be said that the first issue, that of the existence and physical effects of gravitational waves, was solved after Chapel Hill, with agreement among the scientific community. The same cannot be said of the other two issues. The relativity community reached an agreement on the status of gravitational waves in the full nonlinear theory only some years later, thanks to the rigorous work performed in that framework by Bondi, Pirani, Ivor Robinson and Andrzej Trautman, among others. In particular, Robinson and Trautman found exact solutions to the equations of

general relativity describing waves radiated from bounded sources.<sup>45</sup> Furthermore, in the sixties, Bondi, Rainer W. Sachs, Ezra T. Newman and Roger Penrose,<sup>46–50</sup> gave a satisfactory definition of the energy radiated at infinity as gravitational radiation by an isolated gravitating system in an asymptotically flat spacetime. Thus, the modern theoretical characterization of gravitational waves had emerged by the late 1960s.

The last issue took still longer to be settled, since it crucially involved the problem of motion in general relativity and the issue of radiation reaction, whose foundations were still quite shaky.<sup>51</sup> The doubts concerning whether binary systems radiated gravitational energy were fought by crucial empirical input, which came in the mid-1970s with the discovery of the first binary neutron star.<sup>52, 53j</sup> This did not immediately settle the quadrupole formula controversy yet,<sup>54</sup> but it prompted many efforts towards its resolution. The confirmation of came when Thibault Damour<sup>55</sup> showed that there was quantitative agreement between the emission rate computed from the quadrupole formula and observations. In fact, it is only in the final stages of the merging of compact objects that higher (mass and current) momenta need to be included (see e.g. Ref. 56 and references therein).

## 7. Conclusions

In the above pages, we have described the work performed by Richard Feynman in the physics of gravitational waves. We have seen how his attitude towards physics, and towards fundamental interactions, shaped this work, and how he managed to give sound and substantially correct answers to the main theoretical problems of the time. Feynman's physical intuition and sound calculations convinced him early on of the existence of gravitational waves and gravitational radiation. His work contributed to the settlement of the issue, and played a role in triggering the first experimental efforts towards their detection. Feynman did not share the theoretical concerns of most relativists, who continued to argue about other issues, until rigorous solutions and/or experimental input were available, and considered those arguments pointless, harshly criticizing them. This may have been contributed to his loss of interest in the subject, starting from the late 1960s, when he began to be involved to the only fundamental interaction to whose understanding he had not contributed yet, that is, the strong interaction.<sup>5</sup> But that is another story.

## Acknowledgments

The authors would like to thank the staff of the Caltech archives for providing them a copy of Feynman's letter to Weisskopf.<sup>9</sup>

---

<sup>j</sup>In fact, so far, all direct and indirect evidence for gravitational waves has come from binary systems, which hence are the only confirmed sources.

## References

1. R. P. Feynman, The development of the space-time view of quantum electrodynamics, *Science* **153**, no. 3737, 699 (1966).
2. M. Gell-Mann, Dick Feynman-The Guy in the Office Down the Hall, *Phys. Today* **42**, 50 (1989).
3. Letter from Bryce DeWitt to Agnew Bahnson, dated 15 November 1955, cited in Ref. 4, p. 25.
4. C. DeWitt-Morette and D. Rickles, *The Role of Gravitation in Physics*, Report from the 1957 Chapel Hill Conference (Edition Open Access, Berlin, 2011).
5. J. Mehra, *The Beat of a different drum: The Life and science of Richard Feynman*, (Oxford University Press, Oxford, 1994).
6. J. Preskill and K. S. Thorne, Foreword to Ref. 7.
7. R. P. Feynman, F. B. Morinigo, W. G. Wagner and B. Hatfield, *Feynman Lectures on Gravitation*, (Addison-Wesley, Reading, MA, 1995).
8. M. Di Mauro, S. Esposito and A. Nadeo, A road map for Feynman's adventures in the land of gravitation, *Eur. Phys. J. H* **46**, no.1, 22 (2021), [arXiv:2102.11220 [physics.hist-ph]].
9. R. P. Feynman, unpublished letter to Victor F. Weisskopf, February 1961; in Richard P. Feynman Papers, California Institute of Technology Archives, Box 3, Folder 8.
10. D. Kennefick, *Traveling at the speed of thought: Einstein and the quest for gravitational waves* (Princeton University Press, Princeton, 2007).
11. K. Schwarzschild, Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie (On the gravitational field of a mass point according to Einstein's theory), *Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)*, **1916**, 189 (1916), [arXiv:physics/9905030 [physics]].
12. M. D. Kruskal, Maximal extension of Schwarzschild metric, *Phys. Rev.* **119** (1960), 1743-1745.
13. A. Einstein, Näherungsweise Integration der Feldgleichungen der Gravitation (Approximate Integration of the Field Equations of Gravitation), *Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)* **1916**, 688 (1916).
14. A. Einstein, Die Feldgleichungen der Gravitation (The Field Equations of Gravitation), *Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)* **1915**, 844 (1915).
15. A. Einstein, Über Gravitationswellen (On Gravitational Waves), *Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)* **1918**, 154 (1918).
16. A. S. Eddington, The propagation of gravitational waves, *Proc. Roy. Soc. Lond. A* **102**, 268 (1922).
17. A. S. Eddington, *The Mathematical Theory of Relativity*, 2nd edn. (Cambridge University Press, Cambridge, 1960).
18. A. Einstein and N. Rosen, On Gravitational waves, *J. Frank. Inst.* **223**, 43 (1937).
19. A. Einstein and M. Born, *The Born-Einstein Letters: Friendship, Politics, and Physics in Uncertain Times* (MacMillan, New York, 2005).
20. D. Kennefick, Einstein versus the *Physical Review*, *Physics Today* **58**, 9, 43 (2005).
21. G. Beck, Zur Theorie binärer Gravitationsfelder (The Theory of binary gravitational fields), *Z. Phys.* **33**, 713 (1925).
22. A. Mercier and M. Kervaire (eds.), *Fünfzig Jahre Relativitätstheorie* (Birkhäuser, Basel, 1956).
23. F. A. E. Pirani, On the Physical significance of the Riemann tensor, *Acta Phys. Pol.* **15**, 389 (1956), reprinted in *Gen. Rel. Grav.* **41**, 1215 (2009).
24. F. A. E. Pirani, Invariant formulation of gravitational radiation theory, *Phys. Rev.* **105**, 1089 (1957).

25. J. L. Synge, On the deviation of geodesics and null-geodesics, particularly in relation to the properties of spaces of constant curvature and indefinite line-element, *Annals Math.* **35**, 705 (1934).
26. A. Z. Petrov, Klassifikatsiya prostranstv opredelyayushchikh polya tyagoteniya, *Uch. Zapiski Kazan. Gos. Univ.* **114** (8), 55 (1954) English translation: Classification of spaces defined by gravitational fields, *Gen. Rel. Grav.* **32** (8), 1665 (2000).
27. L. D. Landau and E. M. Lifshitz, *The Classical Theory of Fields*, first English edition, Addison-Wesley, Cambridge, 1951.
28. J. Eisenstaedt, La relativité générale à l'étiage: 1925-1955, *Arch. Hist. Exact Sci.* **35**, 115 (1986).
29. J. Eisenstaedt, Trajectoires et impasses de la solution de Schwarzschild, *Arch. Hist. Exact Sci.* **37**, 275 (1987).
30. J. Eisenstaedt, The low water mark of general relativity, 1925-1955, in D. Howard, J. Stachel (eds.), *Einstein and the History of General Relativity*, (Birkhäuser, Basel, 1989), pp. 277-292.
31. C. M. Will, *Was Einstein Right? Putting General Relativity to the Test*, (Oxford University Press, Oxford, 1986).
32. C. M. Will, *The renaissance of general relativity*, in P. C. W. Davies (ed.), *The New Physics*, (Cambridge University Press, Cambridge, 1989).
33. A. S. Blum, R. Lalli and J. Renn, *The Renaissance of General Relativity in Context, Einstein Studies* **16** (Birkhäuser, Cham, 2020).
34. H. D. Zeh, Feynman's interpretation of quantum theory, *Eur. Phys. J. H* **36**, 63 (2011).
35. R. P. Feynman, *Surely You're Joking, Mr. Feynman! - Adventures of a curious character* (W.W. Norton & Co., New York, 1985).
36. W. R. Frazer, Theory of Weak and Strong Interactions, *Phys. Tod.* **14**(12), 80 (1961).
37. M. P. Bronstein, Quantentheories schwacher Gravitationsfeldern (Quantum theory of weak gravitational fields), *Physikalische Zeitschrift der Sowietunion* **9**, 140 (1936), English translation by M. A. Kurkov, edited by S. Deser, *Gen. Relativ. Grav.* **44**, 267 (2012).
38. R. P. Feynman, *Electrostatics, Electrodynamics, Matter-Waves Interacting, Relativity*, lectures at the Hughes Aircraft Company, Notes taken and transcribed by J. T. Neer, 1967-68.
39. H. Bondi, Plane gravitational waves in general relativity, *Nature* **179**, 1072 (1957).
40. J. Weber, Detection and Generation of Gravitational Waves, *Phys. Rev.* **117**, 306 (1960).
41. J. Weber, Observation of the Thermal Fluctuations of a Gravitational-Wave Detector, *Phys. Rev. Lett.* **17**, 1228 (1966).
42. J. Weber, Evidence for discovery of gravitational radiation, *Phys. Rev. Lett.* **22**, 1320 (1969).
43. B. P. Abbott et al. [LIGO Scientific and Virgo], Observation of Gravitational Waves from a Binary Black Hole Merger, *Phys. Rev. Lett.* **116**, 061102 (2016) [arXiv:1602.03837 [gr-qc]].
44. B. P. Abbott et al. [LIGO Scientific, Virgo, Fermi-GBM and INTEGRAL], Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A, *Astrophys. J. Lett.* **848**, L13 (2017), [arXiv:1710.05834 [astro-ph.HE]].
45. I. Robinson and A. Trautman, Spherical Gravitational Waves, *Phys. Rev. Lett.* **4**, 431 (1960).
46. H. Bondi, M. G. J. van der Burg and A. W. K. Metzner, Gravitational waves in general relativity. 7. Waves from axisymmetric isolated systems, *Proc. Roy. Soc. Lond. A* **269**, 21 (1962).

47. R. K. Sachs, Gravitational waves in general relativity. 8. Waves in asymptotically flat space-times, *Proc. Roy. Soc. Lond. A* **270**, 103 (1962).
48. R. K. Sachs, Gravitational radiation, In *Relativity, Groups and Topology*, C. DeWitt and B. S. DeWitt eds. (Gordon and Breach, New York, 1964) pp. 521-562.
49. E. Newman and R. Penrose, An Approach to gravitational radiation by a method of spin coefficients, *J. Math. Phys.* **3**, 566 (1962).
50. R. Penrose, Zero rest mass fields including gravitation: Asymptotic behavior, *Proc. Roy. Soc. Lond. A* **284**, 159 (1965).
51. J. Ehlers, A. Rosenblum, J. N. Goldberg and P. Havas, Comments on Gravitational Radiation Damping and Energy Loss in Binary Systems, *Astrophys. J. Lett.* **208**, L77 (1976).
52. R. A. Hulse and J. H. Taylor, Discovery of a pulsar in a binary system, *Astrophys. J. Lett.* **195**, L51 (1975).
53. J. Taylor, L. Fowler, P. McCulloch, Measurements of general relativistic effects in the binary pulsar PSR1913 + 16. *Nature* **277**, 437 (1979).
54. D. Kennefick, The binary pulsar and the quadrupole formula controversy, *Eur. Phys. J. H* **42** (2017) no.2, 293-310.
55. T. Damour, Gravitational radiation reaction in the binary pulsar and the quadrupole formula controversy, *Phys. Rev. Lett.* **51**, 1019 (1983).
56. L. Blanchet, Gravitational Radiation from Post-Newtonian Sources and Inspiralling Compact Binaries, *Living Rev. Rel.* **17**, 2 (2014), [arXiv:1310.1528 [gr-qc]].