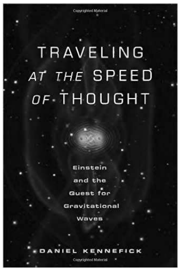
Such a Long Journey

Rajaram Nityananda



Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves
Daniel Kennefick
Princeton University Press, 2007.
Price $35.

Physicists and astronomers are usually presented with a standard, simplified history of gravitational waves (GW) in Einstein's general theory of relativity (GR). The dramatic announcment of the first detection of GW fom a black hole binary came on Feb 11, 2016. In the following weeks, the media have told us time and again that Einstein proposed such waves as early as 1916, and a hundred years later, he was vindicated by the LIGO detection. But nothing could be further from the real sequence of events. This book, published 9 years before the recent announcement, brings out how long and difficult and complex the process of understanding and even accepting the reality of GW was. The outcome was uncertain to many thoughtful researchers as late as the 1970's and even the 1980's, while in parallel, astrophysicists went ahead with calculations of GW effects and comparing them to observation! The book ends with the building of LIGO, optimistically anticipating its eventual success. The author is in a unique position, being exposed to both relativity and history during his stay at the California Institute of Technology (CalTech for short). Kip Thorne, one of his advisors, is a major figure not only behind LIGO but the astrophysical applications of GR in general. Thorne is the middle author of the legendary 1973 textbook *Gravitation* by Misner, Thorne, and Wheeler (MTW), which brought GR to generations of students and research workers after its publication.

Einstein's original calculations of 1916 and 1918 were approximate – as indeed most of his GR work! They clearly needed deeper analysis and confirmation from more accurate work. However, this was not easy, and also, GW were hardly a burning issue in the decades when the quantum theory was being forged by the best minds of that time. Arthur Eddington in England was able to treat the easier problem of a spinning rod emitting waves in his book, but the more astronomically interesting case of two stars orbiting each other was more difficult. He also raised the issue of separating the waviness introduced in the co-ordinate system from genuine waves. Kennefick's book takes its title from Eddington's description of these false waves which can appear in solutions as 'travelling with the speed of thought'. The freedom to choose general co-ordinate systems proved a major handicap in interpreting calculations in GR.

Einstein himself returned to the theme in the 1930's after he had moved to the United States. Nathan Rosen came to work with him in Princeton and was his co-author on two seminal papers. The first was the famous EPR thought experiment which brought out the apparently pardoxical behaviour of quantum systems. The second, in GR, brought in a 'bridge' between two universes, now known as the wormhole. The third paper concerns GW. Einstein and Rosen sought and came up with an exact wave-like solution of the non-linear equations which showed undesirable singularities. Their strong conclusion was that the earlier approximate solution was misleading, and that gravitational waves could not exist. This was submitted to the *Physical Review*. One of the most fascinating parts of the book is the story of this paper.

On the one hand, Einstein and Rosen were not the first to find this solution – Guido Beck had already done so in the 1920's. The referee – now identified by Kennefick's research from the records of the journal as H P Robertson – wrote a detailed criticism. He pointed out that the authors had, unknown to themselves, described cylindrical waves from a line source. He also noted that their singularity could be removed by a change of co-ordinate system – always allowed in GR. Given the stature of Einstein, he recommended revision rather than rejection, and the editor had the courage to back him up. It appears Einstein was furious – he had never been treated like this before. Robertson, independently, had talked to Infeld, another of Einstein's collaborators, who in turn convinced Einstein. The revised version, now as a cylindrical wave solution, went to a different journal without Rosen being in the picture. But Einstein never wrote for the *Physical Review* again! The evidence is that Einstein remained undecided on the existence of GW to the end of his life.

Others were not so cautious. Landau and Lifshitz, writing their text *The Classical Theory of Fields* in the 1940's (hardly an easy time in a Russia invaded by Hitler!) treated the case of a binary star and came up with the same formula as Eddington, when expressed in terms of the quadrupole moment varying with time. Characteristically, they estimated the energy loss to be negligible, and moved on to other topics. After all, they had all of theoretical physics to cover in ten volumes. Their derivation apparently violated the sacred tenets of GR which is to use only geometric quantitites, technically tensors. Their 'pseudo tensor' was an improvement over an earlier such impostor invented by a young Einstein who had no scruples about using it in his early work. V Fock, a Russian mathematical physicist, derived a similar result by insisting that one particular co-ordinate system was preferable to others. True holders of the relativistic faith were therefore suspicious of both these efforts.

Fock's work was one of three independent efforts to solve what is called 'the problem of motion' in GR, which constitutes a major chapter of the book. In one of his last great contributions to the subject, Einstein teamed up with. Leopold Infeld, another refugee from Hitler and Banesh Hoffmann. Their paper, universally known as EIH, contained both conceptual and calculational breakthroughs. Earlier work had treated the motion of test particles in a given spacetime. But conceptually, the particles are themselves sources of gravitational fields. When one has two or more comparable masses, one cannot single out any as test particles. Einstein's long conviction was that his equations relating the field to its sources would themselves yield the equations of motion of these particles. EIH were able to carry out this programme, not just at the Newtonian level but including corrections of the order of $(v/c)^2$ – sufficient to include all astronomical tests of GR up to that time. This is known as the post-Newtonian approach. Apart from Fock, it appears that Eddington and G L Clark (not mentioned by Kennefick) were able to achieve the same goal The date, 1938–39, of this work perhaps explains why further progress was not immediate – the second world war would have clearly pushed such esoteric matters aside.

One of the many fascinating human stories in the book is that of Infeld. As a Jew, he needed Einstein's special intervention to be able to join the university of Berlin in 1920. His early work was with Born on electrodynamics, but his lifelong passion was relativity. After his stay with Einstein in Princeton for the EIH work, Infeld had a position in Toronto, guiding Felix Pirani (see later) among others. But he was hounded out because of baseless suspicions that he would pass on nuclear secrets to the communists in his native Poland. Perhaps, his is the only case of being appointed emertius professor after death – an attempt by the University of Toronto to rectify and atone for its past actions. In our own time, we have seen the royal exoneration of Alan Turning in England.

Just as remarkable is Infeld's role in the gravitational wave story. At Warsaw, he headed the Institute of Theoretical physics, and worked on the problem of motion. Since no wave-like behaviour emerged in this systematic treatment, order by order in powers of v/c, he concluded that other treatments giving waves from binary stars were wrong. However, his own brilliant student, A Trautman, took a different view and was one of the earliest to realise the importance of boundary conditions. Trautman was trained in radio engineering and mathematics, and would have known of the famous Sommerfeld radiation condition which is essential to treatments of diffraction of electromagnetic waves. The EIH approach only took care of the immediate vicinity of the stars, while waves become clearly visible only far away. This turned attention to the behaviour of the gravitational field at large distances from the material sources. Even before Trautman received his PhD, he visited Kings College, London where Hermann Bondi was setting up a strong relativity group. Trautman delivered a series of lectures on relativity to his much senior audience! His contribution to the work at the Kings College is acknowledged in their papers. This part of the story is covered separately (Article-in-a-Box on H Bondi in this issue). Subrahmanyan Chandrasekhar in Chicago was greatly inspired by Trautman's work and acknowledged this in his papers, to which we turn next.

Perhaps Kennefick could have covered Chandrasekhar's contribution to the field in a little more detail than he does; so a digression on this work may be in order. Unlike every other scientist mentioned in the book, Chandra (as he was universally known) entered the field at what would be regarded as an advanced age – nearly sixty! He drew together many threads to weave his magic. Rather than deal with point masses and their associated problems (tamed to some extent by EIH), he chose to deal with perfect fluids, for which the equations of motion follow from the conservation laws built into Einstein's equations. William Burke in CalTech, working with Thorne, had already handled the critical problem of matching the near zone and the wave zone using techniques developed and used in fluid mechanics. (Even the simple-looking problem of dragging a cylinder through a viscous fluid needs such methods, called 'matched asymptotic expansions'). Choices of co-ordinates had to be made at every stage – going up to $(v/c)^7$. For algebraic reasons, Chandra revived what he delicately called the 'Landau Lifshitz complex' which had been shunned by true relativists for twenty years. Another vital ingredient was a graduate student, Paul Esposito, willing to undertake the heroic analytic calculations that this method – or any other for this problem – required. Of course, Chandra checked everything himself as well!

The final outcome was a confirmation of what the less critical had long believed – the Landau Lifshitz formula for energy emitted by a double system. But now, the terms in the near zone producing the damping were exhibited explicitly (as they were in the parallel work by Burke and Thorne and collaborators). To Chandra at least, this put the issue beyond reasonable doubt, and he would continue to apply this formalism (with later students) to astrophysical problems which called for gravitational radiation damping, such as the stability and oscillations of neutron stars.

The whole field took a different turn in the early 1970's with the discovery by Russell Hulse and Joseph Taylor of two neutron stars in a binary system; one of which was conveniently endowed with a clock which could be read from earth – a rotating beam of radio emission. Here was the laboratory needed to test Einstein's theory and very quickly the $(v/c)^2$ corrections were verified – they were huge since the orbit was forty times smaller than that of the planet Mercury, the best previous candidate.

In just four years more, Taylor and Joel Weisberg could announce the successful detection of the energy loss by gravitational waves, via a steady decrease in the orbital period which was around seven hours. This was a very small effect – less than one part in three hundred million per year. But a simple calculation shows that in the roughly five thousand orbits executed in one year, the discrepancy in pulse arrival times caused by this shrinkage is a few per cent of an orbit – much greater than the noise in the observations. Further, there were no free parameters – the relevant quantities like the two masses and the size and shape of the orbit were already determined from earlier work. The gravitational wave emission-induced decay is now verified to an accuracy of better than half per cent, and deservedly won the 1993 Nobel Prize for Hulse and Taylor. Today, it seems obvious that the status of the whole field had to change after this development. Kennefick points out that this took a rather long time – alternative explanations had to be ruled out, and more examples found. By the 1980's, it seems that the whole idea of gravitational radiation from binary systems obeying the quadrupole formula had been accepted.

This did not mean that there was no more work to be done by the theorists. The double neutron star system is weakly relativistic ($v/c \cong 0.002$) but each object is strongly relativistic ($v_{escape}/c \cong 0.3$ from the surface). This needs matching to another strong field zone near each moving object. Gravitational radiation from such compact objects needs a much more sophisticated analysis. Kennefick interviews Thibault Damour who pursued this programme, bringing out once more how subtle the issues involved can become as one goes to higher powers of v/c. The three letter acronym for the work of this school is BDI – Blanchet, Damour, and Iyer (our guest editor for this issue). It has become clear, especially in the recent past after Kennefick wrote, that this is not an academic exercise. When one models two black holes orbiting each other, as in the recent discovery by LIGO, there is no escaping from the strong field region. The model is essential to efforts at detection because it provides a 'template' with which to compare the signal buried in noise – any error in this template translates into inefficient or even failed detection. Even after all the effort that has gone into this field, the final merger of the two black holes defies a pure, first principles analytic approach – the final phase is highly nonlinear, the two black holes are distorted and moving at relativistic speeds. The merger of two black holes was for many years the grand challenge of the field of numerical relativity which puts Einstein's equations on a computer. This required not just faster hardware but better algorithms based on new ideas. The issues of nonlinearity and choice of co-ordinate system, and boundary conditions which plagued analytical efforts for nearly a century show up in computations as well. They have been tamed, just in time for being useful in modeling the detection of a clear signal by LIGO. An analytical framework making optimal use of the information from the post-Newtonian work as well as the numerical work has been proposed by Damour and collaborators and is the state of the art at the present time.

This review has gone beyond the book, expanding into a wider discussion of why it took a hundred years to sort out the theory of gravitational waves. The review also does less than justice to the more technical (at least to a physicist) aspects of history of science that the author devotes considerable space and effort to. The events he relates show that a simple step-by-step progress is a very naive model, and personalities, relationships, and geographical circumstances have played a key role. One fact which does come out is the impact of two major conferences and also the free exchange of ideas and information between the different groups pursuing the same basic problem.

One famous remark of Feynman claims that the philosophy of science is as useful to scientists as ornithology is to birds. Clearly, he just loved to fly himself. But to lesser mortals, it is inspiring to listen to a good story. It is rare that physics has a tale to tell with as many twists and turns as this one. Kennefick's book belongs in serious libraries even for undergraduate students. The book is not too technical for students of history and philosophy of science. They may well benefit from authentic recounting of events which are not too far back in time, so that the voices of the participants and the archival evidence can give a realistic picture – one which questions oversimplified accounts of scientific progress.

In all, a very topical book for postgraduate and even advanced undergraduate physics libraries.

Rajaram Nityananda, Azim Premji University, PES Institute of Technology Campus, Pixel Park, B Block, Electronics City, Hosur Road (Beside NICE Road) , Bengaluru 560 100, India.
Email: rajaram.nityananda@gmail.com