# TRANSFER OF ENERGY BY GRAVITATIONAL RADIATION

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SUMMARY

It is pointed out that gravitational radiation provides a means for converting gravitational energy into energy of other kinds. The history of gravitational radiation theory is briefly outlined, and recent developments, which show unambiguously that gravitational radiation does exist and which exhibit its effects, are explained. Some simple model devices for absorbing energy from gravitational waves and converting it into heat or work are described. Directions for future development are suggested.

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A principal difficulty in the harnessing of gravitation is the problem of releasing stored gravitational energy in a way which would make it possible to convert the released energy into a usable form, such as heat. In this essay the problem of releasing gravitational energy is discussed in the light of recent developments in the theory of gravitational radiation. The importance of these developments is that they show unambiguously what was hitherto uncertain, namely that gravitational waves do exist, that they can be rigourously defined, and that they can carry energy. These developments show also the characteristic differences between gravitational radiation and other kinds of radiation, and so point the way to the discovery of effective methods for the conversion of gravitational radiation energy into mechanical energy or heat.

The theory of gravitational radiation has had a rather confused history. Very early in the development of general relativity theory, a number of approximate calculations relating to gravitational waves were made[1], but it was not until about twenty years ago that any exact investigations seem to have been published. In 1937, Einstein and Rosen[2] investigated certain types of solutions of Einstein's gravitational field equations, and concluded that cylindrical gravitational waves could exist, although neither they at the time, nor Rosen later[3] found what sources might produce such waves. At the same time, Rosen[4] investigated plane-polarized gravitational waves, and came to the conclusion that these could not exist. This conclusion appears to be mistaken, because certain assumptions made by Rosen were unnecessarily restrictive. This will be discussed further below. It had been known for a long time that there were no spherically symmetric gravitational waves.

Thus in 1937, it seemed that gravitational waves of some sorts existed, but others did not. How exactly gravitational waves should be defined was never made entirely clear; what was done was to seek solutions of Einstein's gravitational equations resembling wave-type solutions in Electromagnetic theory. Then in 1938, Einstein, Infeld and Hoffmann[5,6] developed their new approximation method for solving the gravitational equations, and after that the situation became more confused. Wave-like solutions could be found, but it appeared that they could be eliminated by a suitable change of coordinate system, which is always permitted in general relativity theory. A great deal of work by Scheidegger[7], Goldberg[8] and others left it obscure whether gravitational radiation really existed or not. The implication was that gravitational waves were spurious, having no real physical significance.

Now the difficulty about these approaches to the problem was that they were inclined to treat the gravitational radiation problem by analogy with the theory of electromagnetism. However, there are characteristic differences between the two theories. Some of these, like the essential non-linearity of the gravitational field equations, were recognized, but the situation remained obscure. The important difference of which account needed to be taken is the difference between the physical effects of the different sorts of fields. This difference is epitomised in the principle of equivalence, according to which the gravitational field at any point may be eliminated by employing a suitably accelerated reference frame. This is not true of other fields. Another way of stating this difference is to say that not the gravitational field itself, but only its variations from place to place produce absolute physical effects. If we are to explore means of controlling gravitational radiation, it is to these absolute effects which we must look.

The variations in the gravitational field show up physically as differences in the accelerations of free particles in different (although nearby) places. One cannot investigate these features in terms of the gravitational field quantities, as is done in electromagnetic theory, but only in terms of the Riemann tensor, which describes the variations in the field in an absolute way. The present writer has treated the mathematical details of this idea elsewhere.[9]

Having this invariant description of the variations in the field, it is a short step to the description of radiation. One has only to assume, as is natural, that gravitational radiation is propagated with the fundamental velocity which is defined by the null cone. A complete characterization of gravitational radiation in terms of the Riemann tensor then becomes possible. Then the interpretation of the Riemann tensor as the variation in the field shows how gravitational radiation affects the motion of small particles. It is found that the relative accelerations of two such particles, which represent the difference in gravitational force between them, show characteristically different features in the presence of radiation. It is these relative accelerations which provide the key to the problem of energy transfer.

To show the connection, we shall consider a simple model absorbing device. Two free particles by themselves are of no use, as there is no way of extracting from them whatever energy they might absorb. But consider instead two particles connected by a spring. If they receive different accelerations, as they will do if gravitational radiation passes by, then the spring will experience a net force, which will be either a compression or a tension depending on the directions of the accelerations. Any actual spring, not being perfectly elastic, will heat up when it is compressed or extended, and this heat may be used for any desired purpose. Of course we may envisage a variety of other power-generating devices -- the two particles might be connected by rods to a cylinder and piston, for example. The above is supposed merely to be a simple model, showing the possibility of extracting power from a gravitational wave; the actual apparatus used on a large scale would doubtless be more complicated.

Detailed calculations on the transfer of energy by plane polarized gravitational waves have recently been carried out by H. Bondi[10]; these confirm the general expectation described above, namely that energy may be extracted from gravitational radiation by devices of the sort mentioned. It is this calculation which contradicts the work of Rosen mentioned earlier.

The place waves investigated by Bondi have no sources, in the same way as plane electromagnetic waves have none. The question of generating gravitational waves is therefore not solved by this work. However, L. Marder[11] has carried further Rosen's work on cylindrical waves, and has calculated the loss of energy from a cylinder producing gravitational radiation. In this case, therefore, the manner of generation is known, because Einstein's field equations are actually solved inside the oscillating cylinder, but much still remains to be done in investigating the relation between the loss of energy from a radiation body and the absorption and conversion to other useful forms of the energy radiated.

To sum up: It is known as a result of recent work that gravitational energy may be transferred by gravitational radiation and that gravitational radiation energy may be absorbed by suitable devices and converted into energy of other kinds. A general theory of energy generation and of energy balance are still to be developed, but already the controlled transfer of gravitational energy appears in principle possible.

Aside from the engineering problems of gravitational transmitter and absorber design, there remain other more theoretical problems which require to be resolved. It is to be hoped that much light would be thrown on the whole question if the relationship of gravitation to Quantum mechanics were better understood. The exact definition of gravitational radiation which is now possible, and which has been described above, should greatly ease the difficulty of exploring this relationship. Investigations of this question and of the energy balance theory are being carried out.

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