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SUMMARY OF THE GR6 CONFERENCE†

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Being asked to deliver a summary at a conference is certainly a sign of getting old. Feeling still young, I prefer to consider as my duty to give a talk consisting of impressions of the reports presented at the morning sessions of the Conference. Most of these reports were reviews of research done by many people and there is obvious difficulty, even one of a logical character, with summing up the summaries.

Physics is done by people and it would be hard to talk about the Kerr solution without mentioning Kerr. Merely to read the list of people whose important contributions were discussed at the Conference would probably take up all my allotted time. Therefore, no significance should be attached to the number of times any particular name appears in my talk, zero, of course, being a number as good as any. To confuse those who might think otherwise, I decided not to mention the names of the persons who read the invited lectures at the Conference.

In very general terms, my impressions from the Conference are as follows:

First of all, there has been reported significant work in *experiments* and *observations* of general-relativistic effects. None of the described results is in a clear contradiction with Einstein's theory and the precise measurements of the retardation of radar signals [*1*] and of the deflection of radio waves by the Sun [*2*] seem to support the theory rather well. There is a small discrepancy between the Einstein value and one set of measurements of the deflection of radio waves coming from 3C279 [*3*]. There are good prospects for improving the radar measurements so as to reduce the error in the time delay test to 0.3% and to obtain a separation of the general-relativistic effect of perihelion motion from the influence of the quadrupole moment of the Sun. We have also been told that it is conceivable that second-order general-relativistic effects will be detectable in the 1980s.

† The author is indebted to those speakers at the Conference who sent him in advance the manuscripts of their lectures. The present text closely follows the actual, informal talk given at the meeting.

During the last decade, all relativists were following with fascination the *efforts to detect gravitational radiation* [4]. Although most of us, including myself, have been convinced of the existence of this phenomenon in Nature, we were surprised by the numerous coincidences among the events registered by the cylindrical detectors. If these coincidences are interpreted as corresponding to absorption of gravitational waves, then the sidereal time anisotropy of the observations [5] seems to imply an unexpectedly large loss of mass in the centre of the Galaxy [6]. It is encouraging to hear that several teams of physicists, using somewhat different techniques, are about to perform similar observations, and that the Moon will be used as a detector.

I should also like to mention the work of Braginskii [7] who improved on the accuracy of the Eötvös-Dicke experiment and established an upper limit of 0.9×10^{-12} for the relative difference of the gravitational and inertial masses. This is perhaps not so spectacular as the other experiments but really not much less important, if we remember the rôle of the principle of equivalence in Einstein's theory.

Unfortunately, no black or white holes have been identified so far with any degree of certainty. It has been pointed out that our knowledge of white dwarfs and the discovery of neutron stars confirm the correctness of the current theoretical picture of the late stages of stellar evolution, thus making the existence of black holes quite plausible.

Secondly, in my opinion, substantial theoretical progress has been achieved in understanding the process of collapse, the properties of black holes and the occurrence of singularities. A characteristic feature of a large part of the present theoretical research is that it heavily relies on modern mathematics whose use in relativity was initiated by Lichnerowicz. Let me remind you that not so long ago even tensor calculus was frowned upon by many physicists.

By using the notion of an infinite-dimensional differentiable manifold it has been possible to give a precise meaning to Wheeler's idea of *superspace* and to relate the dynamics of the Universe to sets of curves in that manifold [8]. An interesting development in this field consists in considering a reduced, finite-dimensional superspace and in constructing a quantum-mechanical model of the Universe [9]. An important field of research has been initiated by the consideration of stable properties of space-times [10] and of the connection between local physical phenomena and global, geometrical features of manifolds [11]. A significant although not unexpected theoretical result, in a different field, is a clear derivation by Chandrasekhar and Esposito [12] of the *radiation damping force*, in agreement with the prediction of the linearized theory for the flux of gravitational energy radiated by a system of bodies.

Progress in the field of experimental relativity encourages people to have a new look at the *foundations* [13]. It is now possible to rule out a number of theories of gravitation by comparing their predictions with measurements rather than by appealing to the simplicity of the Einstein theory, as was often done in the past.

McVittie's opposition to passing moral judgement on physical theories by referring to them as right or wrong prompts me to the following remark: The notions of truth and falsehood do not apply to theories. By its very nature, any physical theory describes approximately a limited range of phenomena. As a result, the set of all physical theories has a relation of partial order: Einstein's theory is better than Newton's theory but none of them is comparable to quantum electrodynamics. In addition to the obvious reasons for which one theory may be considered as better than another, I should like to add the following criterion: one ought to give precedence to a mathematical model of physical phenomena which is free of elements that cannot be traced to experiments or measurements. Many of the non-Einsteinian theories of gravitation have an auxiliary flat metric although the principle of equivalence makes it impossible to set up experimentally a global, inertial system of reference.

As much as a careful study of all the *rival theories* of gravitation is worth while and may be rewarded by the discovery of new tests of GRT, my personal opinion is that it is unlikely for Einstein's theory to be replaced by a better classical theory of gravitation. Of course it may turn out that some of the quantum gravitational effects will be conveniently described, in the classical framework, by additional terms in the field equations, in a manner considered some time ago by Sexl [*14*] and more recently by Ginzburg and his coworkers [*15*], in connection with the problem of singularities. This would involve a modification of the equations similar to the introduction of non-linear terms into Maxwell's equations, performed to account classically for (some of) the quantum effects of scattering of light on light. Let me also repeat here Bergmann's remark that a theory of gravitation may be called *metric* in at least two senses: firstly, in the sense that it assumes a space-time with a metric related to the proper time similarly as in special relativity; secondly, in a narrower sense, that it also admits a law of parallel transfer with respect to which the metric tensor is constant.

There is a slight modification of Einstein's theory which has a chance of being viable since it does not directly affect the field in empty space. The underlying idea, formulated some time ago by a number of people present at this Conference [*16*], can be traced back to a couple of old papers by Elie Cartan [*17*]. Put in contemporary language, Cartan's idea may be briefly described as follows: In the theory of special relativity, a fundamental rôle is played by the Poincaré group which is a semi-direct product of the Lorentz group by the group of translations. The irreducible representations of the Poincaré group are characterised by two basic invariants, interpreted physically as the rest mass and the spin. In a classical theory of fields, there correspond to these invariants: the tensor density of energy and momentum and the tensor density of spin. In Einstein's theory, the distribution of energy and momentum is dynamically related to curvature. According to Cartan, the density of *intrinsic angular momentum* should be similarly *related to the tensor of torsion* of the space-time manifold. This sounds plausible if we remember that, by the holonomy theorems, torsion bears a similar relation to translations in the tangent spaces as curvature does to Lorentz transformations. The dual connection between curvature and torsion, energy-momentum and spin, and the Poincaré group, is apparent from the diagram

Lorentz tsfms	———	*Curvature*	EINSTEIN ———	*Energy-mom.*	———	*Translations*
	HOLONOMY THEOREMS				NOETHER THEOREM	
Translations	———	*Torsion*	——— CARTAN	*Spin*	———	*Lorentz tsfms*

Very strong magnetic fields, such as those occurring in neutron stars, may be accompanied by a substantial average value of the density of spin. It is conceivable that torsion plays a rôle under such circumstances.

Recent theoretical work on the process of *collapse* and on the structure of *black holes* has yielded a number of startling and significant results. Originally, when the Kerr metric was discovered, it was thought to represent the external field of a very special, axially symmetric, rotating body. Thanks to the work of Ginzburg [*18*], Zel'dovich and his coworkers [*19*], to the theorems of Carter [*20*] and Hawking [*21*], and to the research of the Caltech group [*22*], we are now reasonably certain that the Kerr metric - or the Kerr-Newman metric which is its charged generalisation - represents the limiting form of space-time that surrounds a collapsed body, irrespectively of the initial conditions ('generalized Israel conjecture', cf. [*23*] and the literature quoted there). This result may be considered to indicate that the *'algebraically special'* metrics whose study was initiated by Robinson [*24*] and continued by Newman [*25*], are more relevant physically than was believed in the past. According to Carter and to Debney, Kerr and Schild [*26*], at large distances, the Kerr-Newman solution appears to have a magnetic moment with the same gyromagnetic ratio as the Dirac electron. Our experience with the Kerr solution cautions us against dismissing this result as accidental.

The process of collapse and black holes are good candidates for providing us with *large amounts of energy* in the form of both gravitational waves and ponderable matter [*27*]. A particle penetrating the 'ergosphere' in a Kerr space-time and undergoing a transmutation there, may later leave this region with an energy larger than it had when entering [*28*]. One expects that two black holes merging together will radiate away a substantial fraction of their total rest mass [*29*]. An alternative method of extracting rotational energy from black holes has been recently proposed by Hawking.

The question of *singularities* resulting in collapse and in closed Universes was for some time considered to be controversial. It is now convincingly settled by a number of powerful theorems due to Penrose and Hawking [*30*] and confirmed by independent methods developed by Belinskii, Khalatnikov and Lifshitz [*31*]. According to Hawking and Ellis [*32*], our present knowledge of the 3°K black-body background radiation suffices to prove, on the basis of Einstein's equations, that the Universe is singular. For me, the occurrence of singularities in solutions of the field equations is an indication of the fact that classical general relativity is not applicable at very large densities and curvatures. It is a crucial question to estimate the order of magnitude of curvature at which Einstein's theory fails. One usually says that the radius of curvature in question is of the order of the Planck length.

There are four fundamental numbers, namely

Hubble's constant in cosmological units, $H/(G\rho)^{1/2}$,
the Schwarzschild radius, $2GM/c^2$,
the Chandrasekhar mass, $m^{-2}(hc/G)^{3/2}$,
the Planck length, $(hG/c^3)^{1/2}$,

occurring in computations of general-relativistic effects (ρ is the mean density of mass in the Universe and m is the nucleon mass). The relevance of the first three may be considered as well established but so far Planck's length has not been related to any actually measured quantities.

According to Zel'dovich [*33*] at curvatures of the order of 10^{33} cm^{-1} there should take place *creation* of pairs of particles by the gravitational field. On the other hand, Hawking and Penrose point out that already when curvatures approach 10^{13} cm^{-1}, extraordinary local effects should take place. Therefore, it is conceivable that GRT breaks down at distances much larger than the Planck length.

One is tempted to speculate that the breakdown of classical general relativity at small distances may have to do with the very structure of a differentiable manifold, presumably not suitable to describe space there. There is at least one thing which is wrong with manifolds from the methodological point of view: they rely upon the notion of differentiable functions, and the property of a physical quantity being differentiable cannot be checked in an operational way.

I shall close my short talk with a remark of a rather general nature. In spite of the successes reported at the Conference, I think it is fair to say that research in theoretical physics as a whole is in a poor shape. Progress in understanding fundamental processes, including attempts to construct a quantum theory of gravitation, is rather slow. As much as I would like to offer a remedy, I am only able to formulate a tentative diagnosis. In my opinion, we are often misled by unjustified generalizations to all of physics of notions suitable only in parts of it. Pre-Maxwellian physics was dominated by mechanics. Numerous attempts were made to explain electromagnetic phenomena in terms of elastic forces. It took us a long time to understand - and this became possible only after the advent of quantum mechanics and general relativity - that all the forces that have a chance to be put on the right hand side of Newton's law of motion are of electromagnetic origin. We should remember that the principle of equivalence implies that there is really no such thing as gravitational force. The understanding of interactions in the 20th century physics has been dominated by electrodynamics. We are not so naive as to try to reduce all phenomena to electromagnetism, but we attempt to model all theories after electrodynamics, classical or quantum. When so doing, we rely on many notions, such as that of energy, which may be traced back to that of force. This may be just what is wrong with what we are doing. General relativity, which is the only other fundamental though classical theory, may play a rôle in overcoming our prejudices impressed upon us by electrodynamics.

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