onfigurations, Anti-Gravity and other Aspects in Extended Supergravitie

G W Gibbons

DAMTP

It is a great honour and privilege to give this talk, not least because my own work has been enormously influenced by the ideas of Joel Scherk, to the extent that some of them seem to have become completely "internalised".

As a consequence this is going to be a rather personal and possibly idiosyncratic account of one of his happiest thoughts.

Although I had met Joel and heard him speak about String Theory and Supergravity, it was not until I heard about his ideas concerning Anti-Gravity that I began to study his papers in earnest.

Joel had realised *Phys.Lett* **B88** (1979) 265) that the the vectors that arise in extended supergravity could give a repulsive contribution to gravity which in some circumstances could overwhelm the Newtonian attraction, giving rise to a state of equipoise he called anti-gravity.

Joel was interested in whether there was any experimental evidence for anti-gravity. His work stimulated Riley Newman, an experimentalist, who informed me in a conversation that there was no observational evidence that the sun's mass was out by 40% because it was estimated assuming the exact validity of Newton's Law of Gravitation.

I could not believe such a pessimistic assessment and with Bernard Whiting wrote a Nature paper (*Nature* **291** 626-638) using satellite data to give quite tight bounds on what came to be called the Fifth Force.

The basic idea was to imitate Newton who compared the acceleration of the moon with that of a pendulum bob on earth.

We compared the acceleration of an artifical satellite with the global gravity network constructed by geophysicists.

This rules out an anti-gravity of fifth force contribtion to less that .1% with a Compton wavelength of Kilometres.

All the work of the intervening years has shown no sign of any deviation from Newton's law, either at very small scales (using the Casimir effect) or at very large scales (using Gravitional Lensing) .

I had been invited to lecture at ENS in August of 1980

(An Introduction To Black Hole Thermodynamics. G.W. Gibbons (Cambridge U.) . LPTENS 80/28, Dec 1980. 61pp. Notes of Lectures given at 1980 Summer Inst. of Ecole Normale Superieure, LPT, Paris, France, Aug 4-23, 1980.)

and I had hoped to discuss with Joel that work and also the theoretical ideas behind anti-gravity.

Sadly, Joel died in the May of that year but I continued to be fascinated by his last “Crazy Idea” and worked on it while I was in Paris that summer and in Cambridge in the months that followed..

The most fascinating aspect for me was the fact that in ungauged extended SUGRA, no field carried the charges necessary to cause the necessary repulsion. The charges were what is known as central charges and were necessarily non-perturbative in origin *

I realised that central charges must be, in part, topological and in gravity theories are identical with with Wheeler's oxymoronic concept of Charge without Charge

That is extreme black holes have a natural rôle to play in SUGRA

*Unless like Zachos *Phys.Lett* **B76** (1978) 329) one added gauged hypermultiplets

By then the role of BPS states and Bogomol'nyi bounds in rigid SUSY theories was familar to me from the work of Goddard,Olive Osborn, Witten and others.

I also knew, that because of the Hawking Effect, only extreme, that is zero-temperature, black holes could be stable * and thus possibly qualify as solitons, a point also realised around that time by Hajicek in a non-SUSY context (Quantum Wormholes) (*Nucl.Phys* **B185** (1981) 254)

From my reading in the Library of the ENS I became aware of the fact that SUSY and non-zero temperature were incompatible.†

Thus BPS states must have zero temperature.

*As long as no elementary fields carried their charge

†In fact SUSY generators can't even be defined to act on the Gibbs State

To be supersymmetric a SUGRA solution must admit a Killing spinor ϵ, such that $\widehat{\nabla}_{\mu}\epsilon = 0$. For $N = 0$, this means covariantly constant.

For $N = 2$

$$\widehat{\nabla}\epsilon^{i} = \nabla\epsilon^{i} + \frac{1}{4}\epsilon^{ij}F_{\alpha\beta}\gamma^{\alpha}\gamma^{\beta}\gamma_{\mu}\epsilon^{j} \qquad (1)$$

Moreover, in general, $K^{\mu} = \bar{\epsilon}\gamma^{\mu}\epsilon$ is a non-spacelike Killing vector (and hence only extreme holes can be BPS).

Later I checked that the extreme Reissner Nordstrom black holes admit such a Killing spinor, and that, contrary to a suggestion of Teitelboim (now Bunster), that one *cannot* fit Schwarzschild black holes into a supermultiplet, but that

Extreme Reissner-Nordstrom Black holes form a supermultiplet

These resuts were anounced in a number of meetings during 1981.

The Bogomolny Inequality for Einstein-Maxwell Theory in Monopoles in Quantum Field Theory eds. N S Craigie, P Goddard & W Nahm World Scientific (1982) 137 138 (summary) Proceedings of the Monopole Meeting, Trieste December 1981

Supersymmetric Soliton States in Extended Supergravity Theories Proceedings of the Heisenberg Memorial Symposium eds. P Breit- enlohner & H P Durr Springer Lecture Notes in Physics 160 145151 (1982)

The Multiplet Structure of Solitons in the O(2) Supergravity Theories Quantum struc- ture of space and time eds. M J Duff & C J Isham (Cambridge University Press) 317321 (1983)

However a preprint submitted to *Physics Letters* **B**

Soliton States And Central Charges In Extended Supergravity Theories. G.W. Gibbons (Cambridge U.) . Print-81-0668 (CAMBRIDGE), (Received Sep 1981). 9pp.

It was rejected by a referee in a rather hostile and mildly sarcastic report.

Although at first disapointed, I now realise that to be rejected by *Physics Letters* **B** is something of an achievement.

Rather than engage in a disagreeable dispute, I decided to strengthen my case, and with my then Research Student Chris Hull, managed to prove the Bogoml'nyi Bound for N=2 SUSY

$$M \geq \frac{1}{\sqrt{4\pi G}}\sqrt{Q^2 + P^2}, \tag{2}$$

and find (almost all) the metrics which attain it, using the techniques developed by Witten to prove the Positive Energy Theorem.

A Bogomolny Bound For General Relativity And Solitons In N=2 Supergravity. G.W. Gibbons, C.M. Hull (Cambridge U.) . Print-82-0182 (CAMBRIDGE), (Received Mar 1982). 14pp. Published in Phys.Lett.B109:190,1982

Thaat latter task was completed by Paul Tod *Phys.Lett* **B121** (1983) 241-244

The basic idea is now well known. Formally

$$\{Q_a^i, Q_b^j\} = \delta^{ij} P_\mu \gamma^\mu_{ab} + Q\epsilon^{ij} C_{ab} + P\epsilon^{ij}\gamma^5_{ab} \tag{3}$$

with $a = 1, 2, 3, 4$, $i = 1, 2$ In a supergravity theory the supercharge is given by a surface integral

$$Q^i = \int_{S^2_\infty} \gamma^{[\mu\nu\tau]} \psi^i_\tau d\Sigma_{\mu\nu} \tag{4}$$

Taking a supervariation and integration by parts over a Cauchy surface Σ gives the Witten identity. If black holes are present Σ has an inner boundary, a case worked out in detail shortly after by GWG, Hawking, Horowitz and Perry.

The extension to AdS asymptotics also appears there and was completed by GWG, Hull and Warner. It fully incorporates the Breitenlohner-Fredman bound.

I believe that these papers (and an unpublished paper of Duff, Rocek, Christensen and GWG) were among the first in which the importance and utility of Killing spinors was was realised.

Note that SUGRA Killing spinors are *not* the same as what Penrose calls Killing spinors (which are in effect *tensors*)

Ironically, what Penrose called solutions of the Twistor equation are just the Killing spinors of the conformal group and again not what are called by some conformal Killing spinors.

It is perhaps worth pointng out here that nowadays the *false idea* that BPS implies absolute classical stability has become so widespread. that it is ritually invoked as an almost religious incantation.

Even Minkowski spacetime is unstable to the formation of black holes formed by the collapse of gravitational waves * (a fact emphasised by Wheeler long ago.)

Recent numerical work by Bizon, Schmidt,Chmaj, and GWG on co-hohomogeneity two metrics amply illustrates this point.

**pace Christadoulou and Klainermann*

It is also obvious that a single quantity *defined only at infinity* cannot possibly ensure non-singularity in the interior.

That is,* SUSY cannot be a Cosmic Censor

** pace Kallosh and Linde*

At the quantum level of course things may be different. Hawking radiation may well get rid of the neutral black holes and *if quantum coherence is preserved* one may have quantum stablity.

Put another way, footnote * far from threatening the validity of quantum mechanics, black hole evaporation is *essential* for its preservation.

* *pace* Stephen Hawking

During the middle of 1980's the subject extreme black holes as solitons was also taken up by others, notably the Viennese group, Aichelburg, Embacher and Güven who explored the $N = 2$ situation in great detail, including non-trivial fermionic solutions.

However in almost all other work, one ignores the fermion terms, and simply looks for *commuting* Killing spinors.

Wheeler might have called this Supergravity without Supergravity

I found a great detail of interesting structure duality structure in the next non-trivial, case $N = 4$

Antigravitating Black Hole Solitons With Scalar Hair In N=4 Supergravity. G.W. Gibbons (Cambridge U.) . 1982. Published in Nucl.Phys.B207:337-349,1982

This work attracted the attention of Brietenlohner and Maison with whom I collaborated on case of extended supergravity theories in the four-dinensions, including those coming from strings.

Four-Dimensional Black Holes From Kaluza-Klein Theories. Peter Breitenlohner, Dieter Maison (Munich, Max Planck Inst.) , Gary W. Gibbons (Cambridge U. & Ecole Normale Superieure & Meudon Observ.) . MPI-PAE-PTH-27-87, LPTENS-87-09, Mar 1987. 52pp. Published in Commun.Math.Phys.120:295,1988

Of special interest were the large (sometimes exceptional) duality groups that arose when dimensionally reducing to three dimensions to obtain the equations of motion for stationary black holes.

Black holes transform non-trivially under these solution generating groups

By passing to higher dimensions, I was able ,with Perry, whose work with Gross had uncovered the true rôle of the self-dual Tuab-NUT metrics, to relate the idea weak strong coupling duality

Soliton - Supermultiplets And Kaluza-Klein Theory. G.W. Gibbons (Cambridge U.) , M.J. Perry (Princeton U.) . Print-84-0512 (PRINCE-TON), (Received Jun 1984). 34pp. Published in Nucl.Phys.B248:629,1984

In fact many of the ideas behind S-T-U dualities in string theory were already clear in the work of Cremmer, Julia, Scherk, and Nicolai and de-Wit and fitted this situation like a glove.

These results were reported at various schools

Vacua And Solitons In Extended Supergravity. G.W. Gibbons (Cambridge U.) . Print-84-0265 (CAMBRIDGE), Dec 1982. 13pp. in 'Relativity, Cosmology, Topical Mass and Supergravity, ed. C. Aragon, World Scientific. Lectures given at 4th Silarg Symposium, Caracas. Published in Caracas Sympos.1982:163

Aspects Of Supergravity Theories. G.W. Gibbons (Cambridge U.) . Print-85-0061 (CAMBRIDGE), Jun 1984. 53pp. Three lectures given at GIFT Seminar on Theoretical Physics, San Feliu de Guixols, Spain, Jun 4-11, 1984. Published in GIFT Seminar 1984:0123 (QCD161:G2:1984)

Solitons And Black Holes In Four-Dimensions, Five-Dimensions. G.W. Gibbons (Cambridge U.) . PRINT-85-0958 (CAMBRIDGE), (Received Dec 1985). 14pp. In *De Vega, H.j. (Ed.), Sanchez, N. (Ed.)

but in pre-internet days their circulation was limited.

In (1981) Manton introduced a new idea into soliton physics: that of slow geodesic motion on a moduli space* and this was readily extended to include black holes

The Motion Of Extreme Reissner-Nordstrom Black Holes In The Low Velocity Limit. G.W. Gibbons, P.J. Ruback (Cambridge U.) . PRINT-86-0409 (CAMBRIDGE), (Received May 1986). 12pp. Published in Phys.Rev.Lett.57:1492,1986

The job was completed by Ferrell and Eardley *Phys.Rev.Lett* **59** (1987) 1617, and rather later for Maxwell-dilaton theory by Shiraishi *Nucl.Phys* **B402** (1993)399-410

*more properly modulus space

This turned out to be a very rich subject reviewed in

Moduli Spaces, Geodesics And The Slow Motion Of Solitons. G.W. Gibbons (Cambridge U.) . 1988. In *Swansea 1988, Proceedings, Mathematical physics* 342-345. (see Conference Index).

and later elaborated in

HKT and OKT geometries on soliton black hole moduli spaces. G.W. Gibbons, G. Papadopoulos (Cambridge U.) , K.S. Stelle (Imperial Coll., London) . DAMTP-R-97-28, IMPERIAL-TP-96-97-50, Jun 1997. 55pp. Published in Nucl.Phys.B508:623-658,1997 e-Print Archive: hep-th/9706207

By the end of the 1980's the grounding of the theory of BPS solutions in SUGRA was well established but had failed to make much headway in the wider community, particularly those working in String Theory. The ideas had already been applied to Cosmic Strings in Bogomolny Bounds For Cosmic Strings. A. Comtet (Orsay, IPN) , G.W. Gibbons (Ecole Normale Superieure & Cambridge U.) . LPTENS-87-30, IPNO-TH-87-66, Sep 1987. 20pp. Nucl.Phys.B299:719,1988

but the subject attracted a wider attention when applied to Superstrings in

Superstrings And Solitons. Atish Dabholkar (Princeton U.) , Gary W. Gibbons (IHES, Bures-sur-Yvette) , Jeffrey A. Harvey (Chicago U., EFI) , Fernando Ruiz Ruiz (Cambridge U.) . PUPT-1163, DAMTP-R-90-1, EFI-90-11, (Received Apr 1990). 26pp. Nucl.Phys.B340:33-55,1990

From then on, the concept of BPS states in SUGRA seem to have entered the general conciousness with many people making contributions.

Renata Kallosh (*Phys.Lett.* **B282** (1992) 80-88) entered the game in 1992 by using superspace techniques to establish the vansihing of quantum corrections in $N = 2$ and then going on to establish many things about SUSY black holes with her students Thoams Ortin, Amanda Peet and Barak Kol, including an attempt with Andre Linde to elevate SUSY to the rôle of a cosmic censor.

Around 1993 Cvetic, Griffthes and Rey looked at SUGRA domain walls.

My old idea relating solitons to vacuum interpolation between two SUSY vacuua was revised in

Vacuum interpolation in supergravity via super p-branes. G.W. Gibbons, P.K. Townsend (Cambridge U.) . DAMTP-R-93-19, (Received Jul 1993). 8pp. Phys.Rev.Lett.71:3754-3757,1993 e-Print Archive: hep-th/9307049

Highlighting the rôle of the role of $AdS_p \times S^q$ SUSY ground states as near horizon geometries with enhanced SUSY.

A big boost for the subject came in 1994 with Sen's work on S-duality in Yang-Mills theory

and Hull and Townsend's work on the Unity of superstring dualities

But the flowering of the subject has come about with the recognition of the importance of branes in SUGRA pioneered by Townsend, Sezgin, Duff, Pope and other supergravity practioners and elaborated on by Horwowitz and Strominger among others.

String theorists were eventually reconclied to their existence by the work of Polchinksi on Dirichlet Branes and Ramond-Ramond charges in 1995

From the standpoint of soliton theory, Ramond-Ramond charges are just a case of Charge without Charge and can be carried by extended p-brane solutions. The BPS solutions must be extreme and will have near horizon geometries of the form $AdS_p \times S^q$.

The 3-brane solution of Horowitz and Strominger(1991), obtained by oxidizing a black hole solution of Gibbons and Maeda(1988) to ten dimensions, corresponds to $p = q = 5$.

This fact was brilliantly made use of by Maldacena in 1997 in his work on The Large N limit of superconformal field theories and supergravity better known as the AdS/CFT correspondence.

Just a year earlier, in 1996 Strominger and Vafa's article on Microscopic origin of the Bekenstein-Hawking entropy and Callan and Maldacena's dual 5-brane approach had at last made contact between, macroscopic black hole entropy and microscopic staring states by considering the central charges of a anti-gravitating configuartion of branes and strings .

Antigravity was indeed a crazy idea, but 27 years later I think we can agree that it was crazy enough.