Strong Fields, Integrability and Strings

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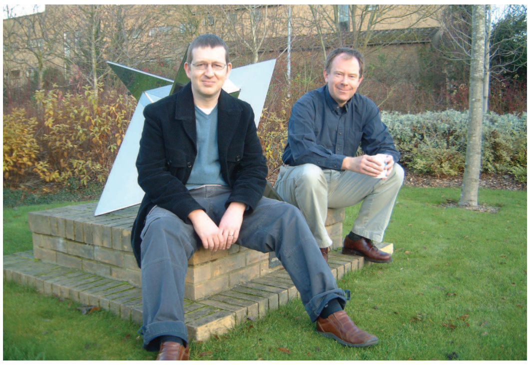
Report from the Organisers:
N Dorey (Cambridge), S Hands (Swansea) and N MacKay (York)

SJ Wilkinson



N Dorey and N MacKay

Theme of the Programme

For over 25 years, Quantum Chromodynamics (QCD), the gauge theory of quarks and gluons based on a gauge group SU(3), has been the accepted theory underlying strong interactions. However, many fundamental questions, which impact on the early universe as well as particle physics, still await satisfactory explanation: the masses of the observed particles; the nature of colour confinement of quarks through chromoelectric flux tubes and its relationship to strings; and the properties of the deconfined 'quark-gluon plasma' (QGP), the object of experiments at RHIC and the LHC.

To date the most systematic way of studying QCD non-perturbatively is via Lattice QCD, with fields defined on a Euclidean space-time lattice. Using Monte-Carlo importance sampling, much progress has been made in reproducing the hadron spectrum at the 5–10% level, in calculating important matrix elements, in identifying topologically interesting field configurations, and in bulk thermodynamics. Currently much attention is focussed on light fermions with the correct global chiral symmetries, which are required both for prediction of physics beyond the standard model, and for the formulation of supersymmetric (SUSY) models.

A productive avenue explored in analytic approaches is the observation that some dramatic simplifications occur in QCD-like theories with a large number N_c of colour charges. Perhaps the most surprising recent result is Maldacena's 1997 conjecture that gauge theory and string theory are equivalent in a particular model (strings on $AdS_5 \times S^5$ and N = 4 SUSY gauge theory) with the result that strongly-interacting gauge theory can be explored in the weak curvature limit of string theory, and vice versa, that gauge theory can shed light on information loss from black holes and provide a possible non-perturbative definition of string theory in certain space-times. This 'holographic principle' realises 't Hooft's vision that the large-N_c limit would converge into a string description of QCD.

The gauge theory/string theory correspondence has led to many powerful and unexpected results in strongly interacting theories, e.g., analytic predictions for the glueball spectrum; studies of chiral symmetry breaking and pion dynamics; and the calculation of the viscosity of N = 4 SUSY gauge theory, an effective model of the QGP.

In parallel, work on integrable models has provided a rich variety of insights into the analytic and algebraic structure of quantum systems and various beautiful connections between different branches of mathematical physics and mathematics. In recent years a recurring theme in the gauge/string correspondence has been the presence of integrability. For example, recent progress uses the techniques of integrability (exact S-matrices and the Bethe ansatz) to posit exact results for the energies of certain string states and thus (on the gauge side) the scaling dimensions of the corresponding operators. It seems that integrability plays a ubiquitous and powerful role in fundamental physics.

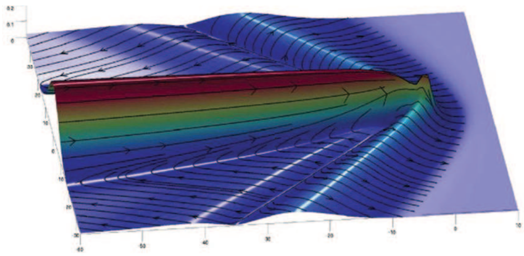
Structure of the Programme

The programme included two workshops and a 10-day school. We planned a rough schedule of themes: strongly-interacting thermodynamics and vacuum structure; the relation between gauge and string theory; and integrable models. Flexibility and serendipity brought together workers from different backgrounds – a major success of the programme. Rapid progress in the year leading up to the programme underlined the value of participation by experts in gauge/string duality.

As well as the typically daily seminar, some participants led extended introductory lectures and subsequent discussions: for instance, Aharony covered holographic models of deconfinement and chiral symmetry restoration in QCD, and Hanany covered dimers, quivers, counting problems and Hilbert schemes.

The first workshop, *Exploring QCD: Deconfinement, Extreme Environments and Holography* (organisers Evans, Hands, Teper), attracted 75 participants and 46 talks were given. It was especially topical given the conjunction of: heavy-ion collision experiments at RHIC; the imminent start-up of LHC; the exploitation of multi-teraflop computing resources; and recent dramatic advances in understanding gauge/gravity duality. Several talks focused on applications of the latter to study transport and the passage of heavy quarks through a strongly-interacting non-abelian plasma. Others reported progress in extending the holographic principle to non-supersymmetric theories. The workshop succeeded in its aim of initiating and sustaining dialogue between phenomenologists, lattice experts and gauge/string theorists.

The second workshop, *Integrability and the Gauge/String Correspondence* (organisers Dorey, MacKay, Tseytlin, Zarembo), attracted 83 participants and 40 talks were given. Talks covered the spin-chain of operator-traces in N = 4 SUSY gauge theory, the hidden integrability of the AdS string, as well as the techniques of classical and quantum integrability. The mix of expertise from gauge fields of strings (especially in AdS/Conformal Field Theory) and the integrable models community worked extremely well, with extended and lively discussions.



Energy flux for $v = 0.75$

LG Yaffe, PM Chesler

Energy flux in the wake of a heavy quark moving through a maximally supersymmetric Yang-Mills plasma at three-quarters of the speed of light. The flux magnitude is both colour-coded and indicated by the height of the surface; flow lines show the direction of the flux. Clearly visible in the flux is the Mach cone, as well as the diffusive tail behind the quark.

The school on *Gauge Fields and Strings* organised by D Tong provided both introductory and advanced lectures on topics related to the recent explosion of activity at the interface between gauge and string theory. Ten invited lecturers, including Microsoft Research Fellow Larry Yaffe, each gave 3–4 talks to an audience which included 47 registered students and younger researchers, many from the 29 programme participants present at the time, and 25 students from DAMTP at Cambridge. The online videos are a valuable resource. In total, 42 talks were given. Popular features included several ‘gong shows’ where students were given a glass of wine and invited to present their own research in the most exciting fashion possible!

Finally, with the help of the London Mathematical Society, we organised a ‘Spitalfields Day’ of talks aimed at undergraduate and postgraduate students, given by Evans, Shifman and Gorsky. The highlight was a talk entitled *The Coming Revolutions in Fundamental Physics* by 2004 Nobel Laureate and Rothschild Visiting Professor David Gross, a fitting occasion to mark the Institute’s 15th anniversary, and so popular that it had to be relocated to a larger lecture theatre.

Outcomes and Achievements

The programme attracted a total of 254 researchers, including 124 workshop participants, with 51 papers or preprints listed in exit questionnaires. Participants gave 35 invited talks at UK universities, including Brunel, Cambridge, Cardiff, Durham, Heriot Watt, Imperial College, King's College London, Liverpool, Oxford, Plymouth, Queen Mary, Swansea and York.

Given the nature of the programme and its success, it is difficult and somewhat invidious to pick out just a few outstanding topics for special mention. Some highlights include:

- A clarification of the relation between gravity backgrounds including black holes and the hydrodynamic regime of strongly interacting gauge theories, enabling the calculation of transport coefficients and sound propagation in the deconfined phase of gauge theories, which underpins the idea of the strongly interacting quark-gluon plasma (Policastro, Starinets, Minwalla, Stephanov, Reall, Hubeny, Gibbons, Rangamani).

- A study of the propagation of heavy quarks using the techniques of gauge/gravity duality, in particular showing the development of a Mach cone in the particle's wake, which may conceivably help in the interpretation of heavy ion collision data from RHIC (Yaffe, Vuorinen).

- The first steps towards a numerical calculation of transport coefficients have been made by relating Euclidean Green functions, calculable by numerical simulations of lattice QCD, to real-time response functions via the Kubo relation (Meyer, Aarts).

- The inclusion of fundamental, as well as adjoint, degrees of freedom in AdS/CFT models has expanded the scope of the predictions accessible to gauge/gravity duality, for instance, permitting the thermodynamic phase diagram of QCD-like theories to be probed (Aharony, Erdmenger, Evans, Peeters, Zamaklar). This can then be compared with lattice gauge theory simulations with non-zero baryon chemical potential (de Forcrand, Philipsen, Hands).

- Developments in simulating lattice models with exact supersymmetry, aided by theoretical ideas related to twisted or topological field theories and orbifolding, together with recent algorithmic advances in the simulation of light quarks. There has also been progress in understanding the relation between the various different methods currently being explored (Akemann, Catterall, Damgaard, Matsuura).

- Increased activity in simulating QCD-like theories with varying numbers of colours and with quark fields in varying representations of the gauge group. This has been inspired by the need to challenge recent analytic progress in understanding QCD in the large-N_c limit, but also has a phenomenological application in aiding truly non-perturbative study of walking technicolor scenarios for electroweak symmetry breaking, which may be tested shortly at LHC (Del Debbio, Bringoltz, Teper, Lucini).

- Enhanced understanding of the phase structure of Super Yang–Mills theory: specifically, exploring the relation between Polyakov–Maldacena loops in the supergravity duals and ordinary Wilson loops in the gauge theory. Of particular significance is the eigenvalue distribtion of the P-M loops, which shed light on how the phase structure of SYM theory changes between weak and strong coupling (Aharony, Hartnoll, Gursoy, Kumar). A related issue in SYM theory is the connection between Wilson–Maldacena loops with cusps and multi-gluon scattering amplitudes (Branhuber, Alday, Tseytlin, Travaglini, Roiban).

- Identification of a new supersymmetric gauge theory in three dimensions starting from a field theory model for M2-branes (Bagger, Lambert).

- Progress towards treating strings on $AdS_5 \times S^5$ in a manner which retains 2D Lorentz covariance, by using Pohlmeyer's reduction technique for integrable sigma models to reformulate the string sigma model using only the physical degrees of freedom (Grigoriev, Tseytlin).

- Use of the integrability of the sine-Gordon model, and its connection with $AdS_5 \times S^5$ strings, to construct two-magnon string states and thereby improve our understanding of magnon interactions and multi-magnon states (Klose, McLoughlin, Mikhailov, Schafer-Nameki).

- Development of a generalised scaling function for planar N = 4 SUSY Yang–Mills which yields predictions for a new one-parameter family of observables computable in the dual string theory (Staudacher and Freyhult).

A full report on this programme can be found at

www.newton.ac.uk/reports/0708/sis.pdf