Particle physics

Where now with superstrings?

from Robert Walgate

LITTLE more than a year since superstring theory, the best attempt yet at a 'theory of everything', began to drag particle theorists into its net, superstrings are still "the only game in town" for the unification of forces, including gravity, in a quantum framework. So says Steven Weinberg (University of Texas), who with Abdus Salam and Sheldon Glashow developed the first modern unification of forces, 'electroweak' theory, that combines electromagnetism and the weak interaction. Weinberg gave the summary talk at a recent high-energy physics conference*, where it was clear that superstrings have become an important part of particle physics.

The basic idea underlying superstring theory is that the Universe is a world of many more dimensions than the four now apparent (the number ten is now usually favoured) inhabited by myriad, almost infinitesimal, elastic strings. These strings, sometimes looped, charged, spinning and vibrating, interact to pull the extra (usually six) dimensions into a tiny, closed structure full of gaps and holes that is left attached, almost like hair, to the remaining still-extended four dimensions, a process termed compactification. Particular arrangements of this stringy hair, such as a string winding once through a particular kind of six-dimensional hole, then lead to the particles we see.

But the theory has its problems. One of them is its uniqueness: the meeting showed that there are at least six candidate theories, all of which seem (so far) to be self-consistent and free of 'anomalies', the hidden quantum violations of charge and energy–momentum conservation that have dogged all other attempts at unification. According to Weinberg, John Schwartz, who with Michael Green launched the first more-or-less realistic anomaly-free string theory, said at the meeting that the number of candidate theories (which differ in the number of dimensions, the exact constitution and charges of the strings) could even increase, although it could decrease again if inconsistences are found in some versions.

Weinberg says the meeting was not perturbed by this development. All the versions of the theory may be the same in substance, each possibly being a different dynamical solution of a single underlying theory. This, according to one controversial view, could take the form of a string theory originally introduced many years ago as a model of the strong interactions: a bosonic string in 26-dimensional space-time. Furthermore, another problem of non-uniqueness in superstring theory, the variety (thousands) of possible four-dimensional worlds it allows, is showing some signs of resolution. "The trouble with superstring theory, though this may not last, is that there don't seem to be any easy problems" says Weinberg. A theory should not be thrown away because it is difficult to use (the equations of hydrodynamics remain true even though it is almost impossible to calculate turbulent flow), but most difficult theories, including hydrodynamics, have certain key simple predictions through which they can be tested. But for superstrings "Schwartz said, and I agree, that there seem to be no decisive tests in sight". So superstrings remain with the theorists.

Weinberg points out that superstring theory has also disappointed early hopes of a natural solution of the 'cosmological constant problem', the question of how gravity behaves as if the vacuum is empty although in all unified field theories it is packed with a hornets' nest of forces and curvatures. Nevertheless the theory has had "many qualitative successes" and remains "a very beautiful theory, partly because of its logical rigidity".

Could there be experimental tests of the existence of strings? The phenomenology of the theories remains "murky", says Weinberg, precisely because of the number of ground-state 'worlds' which are still in practice indistinguishable. There may still be thousands of ground states to explore. One such exploration reported at the meeting requires a "great deal of mathematical virtuosity"; the resulting 'world' is "very encouraging, in that there are no problems like the proton decay being too fast, and the general pattern of quark and lepton masses looks vaguely reminiscent of the real world". But there are many 'worlds' yet to explore, each requiring its degree of virtuosity, and we may not be able to muster the labour to find the solution.

Although no projected experiments can bear directly on superstrings, there are nevertheless still some experiments of great interest that can be done. Next year should see the first experiments on the Fermilab Tevatron Collider, which will reach 2-TeV collision energies between protons and antiprotons, and the Stanford Linear Collider (SLC), which will be a 'factory' of Z^0's, the intermediate vector bosons that mediate the neutral part of the weak interaction. The prospect of these experiments, particularly those at the Tevatron, "loomed" over the conference, says Weinberg. Although they are unlikely to reveal anything directly about superstrings, the SLC experiments should provide "exquisitely detailed" data on the decays of the Z^0, thus producing fine tests of the 'standard model', (the Weinberg–Salam electroweak theory plus quantum chromodynamics for the inter-quark force). Experiments, especially those with the Tevatron, "are going to settle the question of whether or not there is a vestige of supersymmetry at low energies".

This bears on string theory because superstrings are also supersymmetric, in that for every low-energy particle they create they also create a massive 'superpartner', a partner differing only in its higher mass, spin and quantum statistics. (Thus, if a particle obeys the Pauli exclusion principle, like the electron, its superpartner will not; and if a particle does not obey the exclusion principle, like the photon, its superpartner will do so.) Superpartners are useful in that they help explain why the weak interaction separates from the electromagnetic at energies of just a few hundred GeV, compared with the 10^{15} GeV or so at which electroweak forces separate from colour (the 'hierarchy problem'). However, superpartners only do the trick if their mass is sufficiently low. The Tevatron should see squarks, the superpartners of quarks, if their masses are less than 200–300 GeV, "a very plausible mass for them to have". If the Tevatron sees no superparticles, supersymmetry will lose its value in the hierarchy problem, and hence half its motivation. If the superpartners are found, on the other hand, we will know the masses and interactions of these long-dreamed-of particles, and "I can't even imagine what impact that's going to have on our models" says Weinberg. Superstring theory, however, could survive a non-discovery: the Calabi–Yau compactifications of the six extra dimensions were chosen, in part, to produce low-energy supersymmetry. It should be possible to find other classes of solution to the superstring equations that push the superpartner masses higher.

On other experimental issues, Weinberg is convinced by contributions at the meeting that there is a scientific "no-lose theorem" for results from the proposed superconducting supercollider (SSC), a 20-TeV collider now awaiting a decision on its construction from the US Department of Energy. Rigorous calculations in which space-time is approximated as a lattice (a common technique in modern quantum field theory) show that the SSC must reveal the origin of the symmetry breaking that divides electromagnetism from the weak interaction at low energies. This mechanism could either involve a vacuum full of a 'Higgs field', or a new superstrong 'technicolour' force that could lead to strong interactions between intermediate vector bosons. According to

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this no-lose theorem, the Weinberg–Salam electroweak theory, which is a low-energy approximation invoking the Higgs mechanism, must break down to some 'new physics' at an energy that depends on the mass of the lightest observable Higgs particle. If the Higgs mass is low (100 GeV), the breakdown does not appear until 10^{19} GeV where quantum gravity enters and new physics is certain. If the Higgs mass is only 10 times higher, new physics sets in "almost immediately". In either case, the corollorary for the SSC is that there will be something fundamental to observe: either Higgs at 100 GeV; or both Higgs and the new physics, possibly technicolour.

Solar neutrinos were also central to discussions at the meeting. The new 'resonance' mechanism explains the low incidence of solar neutrinos in Raymond Davis's electron neutrino detector at Homestake Mine, South Dakota in terms of a resonant, efficient conversion of solar electron neutrinos into higher-mass neutrino species in the Sun. This mechanism requires the neutrinos to have masses that turn out to be of exactly the order predicted by a wide class of unified field theories, according to Weinberg, who presented very general arguments that the mass of the heaviest neutrino should be around the square of the top quark mass divided by the grand unification scale (about 10^{15} GeV). This works out at around 10^{-3} eV, whereas the solar resonance model is tolerant of a range from 10^{-3} to 10^{-5} eV, depending on mixing angles between neutrino types. Weinberg argues, therefore, that a test of the resonance model is now "as important as anything else in particle physics". Several experiments are already at proposal stage. The best method would be to look for weak neutral current interactions of the solar neutrinos arriving at the Earth, Weinberg suggests, because all the incoming neutrinos would interact equally, the neutral current being 'democratic' in neutrino types.

If the Davis experiments, which measure charged-current interactions, are seeing few electron neutrinos because there are fewer of these particles produced in the solar core (perhaps because the temperature is lower than expected) then a neutral current experiment will see the same number. But if the threefold depression below predicted rates that Davis sees is caused by the conversion of two-thirds of the electron neutrinos to other neutrino types, then a neutral current experiment will see three times Davis's signal. Weinberg says that this experiment "may be our lucky break", the only indication of the grand unification of forces that comes down to us from 10^{15} GeV, now proton lifetimes seem too long to detect. □

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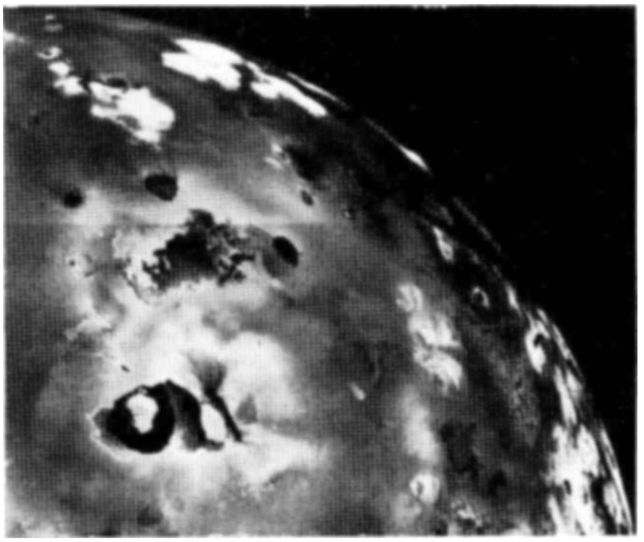
Planetology

Sulphur and volcanism on Io

from David A. Crown and Ronald Greeley

SULPHUR on Io was suggested even before Voyager 1 and 2 flew by the jovian system in 1979[1,2], and although its existence is now generally accepted, its precise role remains controversial. The morphology of volcanic landforms argues for a surface formed by silicate volcanism, whereas spectral data indicate a surface dominated by sulphur (see ref. 3 for review). Lunine and Stevenson[4] recently presented a model for hot spots, regions of intense volcanism on the surface of Io, as lakes of molten sulphur.

Active volcanoes were observed on Io during the Voyager I and 2 missions and are attributed to the dissipation of tidal energy resulting from the configuration of Io's orbit in the jovian system[5]. McEwen *et al.*[6], using Voyager infrared interferometric spectrometer results and multispectral data, correlated dark calderas with areas of high heat flow. Recent experiments concerning the optical properties of sulphur are consistent with this correlation and indicate that molten sulphur on the surface of Io would be black as observed by Voyager instruments[7].



Voyager I mosaic showing the eruption of Loki (lower left). Plumes emerge from a linear black fissure approximately 200 km long. The crescent-shaped large dark patch to the left of the fissure may be a lava lake with a section of solidified crust in its interior. Other vents are seen in the image as dark, nearly circular patches surrounded by lava flows and volcanic plains. The original mosaic was processed by A.S. McEwen (Arizona State University) and the US Geological Survey.

Lunine and Stevenson explain the hot spots using a model for a convecting sulphur lake heated by an underlying silicate magma chamber. The model considers the physical and chemical processes in convective sulphur lakes, including the thermodynamic and transport properties of sulphur and the effects of some possible impurities. In addition, the model takes into account the physics of convecting, boiling systems and the transport of vapour away from such systems. The authors suggest that the temperatures and thermal fluxes observed in the Loki Patera region of Io (see figure) are consistent with their model of a convecting sulphur lake and that the total thermal flux is consistent with the maximum that could be derived from a convecting silicate magma chamber. Their model also explains the distribution of thermal energy around Loki Patera observed during the Voyager missions and indicates that evaporation constrains the maximum surface temperature of a sulphur lake under steady-state conditions.

Lunine and Stevenson's model provides the means to relate the surface heat flow detected by Earth-based infrared observations to changes in the temperature of a sulphur lake and variations in the output of silicate magma chambers in Io's crust. The authors estimate that if lake renewal or magma chamber lifetimes are limited to 1 – 100 years, then changes in the thermal output in the Loki Patera region could be detected. Continued Earth-based observations at infrared wavelengths are important to distinguish between: (1) high temperature (600 K) outbursts isolated from the Loki region (volcanic eruptions); (2) independent changes in warm or hot components in the Loki region (the warm component, the result of the latent heat released on condensation of evaporative sulphur in the atmosphere surrounding a sulphur lake, and the hot component caused by the heat released by convecting molten sulphur); and (3) changes in sulphur lake temperature and the corresponding evaporative sulphur flux. Consequently, Earth-based monitoring could provide important information about Io's thermal output and volcanic activity.

Lunine and Stevenson also consider the effects of impurities such as sodium polysulphides. If the base of a sulphur lake became enriched in sodium polysulphides, convection of this material might