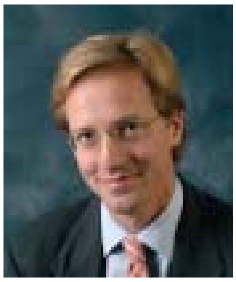
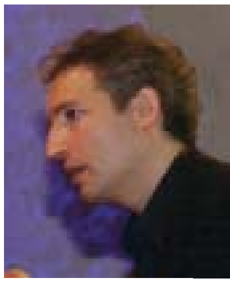
Concerted voices on STRINGS

Quantum mechanics describes the world of the infinitely small, explaining the very special interactions at particle level. Einstein's theory of general relativity applies to the infinitely big, combining space and time within a single entity (space-time) whose deformation explains the universal gravitational attraction between the large galactic and stellar objects in the universe. The major challenge for contemporary physics is to make the link between these two approaches and formulate a new unified theory – to which scientists have already given the name 'quantum gravity'. Initiated in the 1970s, the development of the 'strings' mathematical approach is raising huge hopes of achieving this. Explanations from Robbert Dijkgraaf, Professor at Amsterdam University (NL), and from Brian Greene, Professor at Columbia University (US), two of the guests at the Solvay Council who spoke at the public conference that closed this scientific meeting.



Robbert Dijkgraaf



Brian Greene
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Why are physicists so 'obsessed' by this Grail of quantum gravity?

Robbert Dijkgraaf: Because the duality between the two approaches, quantum and gravitational, both born during the 20th century, appears intolerable. Nature is not divided into two parts and one can no longer be satisfied by describing it with two distinct theories – one valid on the small scale, the other on the large scale – which do not speak to each other. If we do not overcome this contradiction, we cannot improve our knowledge of the Universe, the Big Bang and elementary particles.

Brian Greene: I would add that there is no clear border between what is 'small' and what is 'large'. This impossibility of demarcation is one of the reasons why we need this new framework of a quantum gravity theory.

Among all the attempts to unify quantum mechanics with General Relativity, string theory seems the most promising. What are its principles?

R.D.: String theory rests on the fact that, in the quantum world, things are 'fuzzy'. What does that mean? Let us imagine that one progressively zooms in on a photograph. After a certain point, one no longer sees a single image but only black, white or coloured fuzzy 'entities', similar to those that digital technologies call pixels.

Thus, when combining the theory of general relativity (describing space and time) with the quantum principle (according to which things become fuzzy at very small scales), it is more realistic not to regard particles as perfectly defined points. String theory makes it possible to account for their intrinsically fuzzy nature by describing them as kinds of small strings (one dimensional objects) instead of perfect points (zero dimensional objects).

This approach is fascinating because, if you assume that particles are strings, then mathematics allows you to recover the general relativity equations without any additional assumptions. When physicists discovered this possibility thirty years ago, they realised that they had found a significant part of the puzzle to combine general relativity with quantum mechanics. It was a new way of considering Einstein's theory.

Where are we today?

B.G.: String theory is a wonderful mathematical construction with beautiful equations that make it possible to predict the existence of new particles that no-one has yet observed. The challenge now is to support these predictions with experimental evidence.

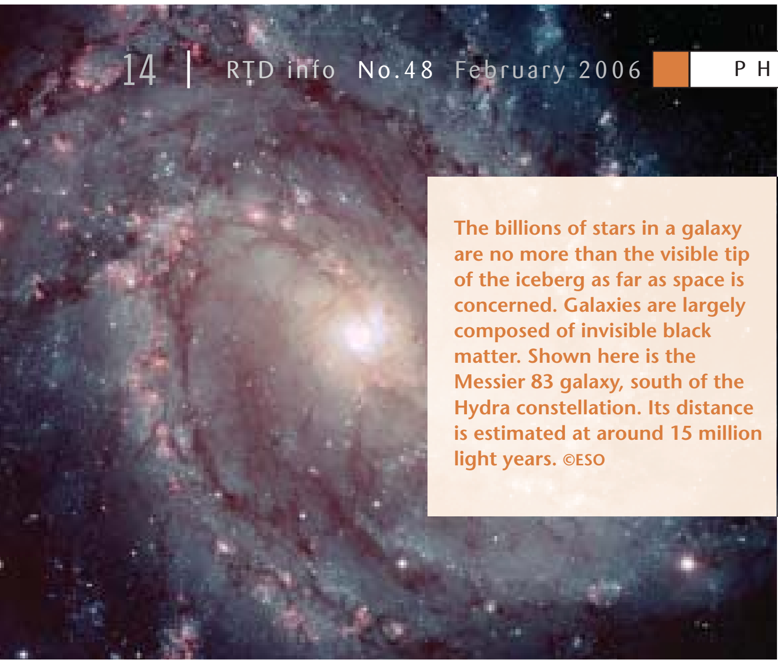
How can such evidence be obtained?

B.G.: The hope is that amongst the debris of high-energy particle collisions – such as the protons which will collide at high speed in the future Large Hadron Collider (LHC) at CERN – we will find these undiscovered particles, also known as *supersymmetric particles.*

Another possibility lies in the fact that string theory predicts a Universe whose space has more than three dimensions. So, at high energies, some particles could be ejected out of our three-dimensional space taking their energy with them. In this case, the detector would record less energy at the end of the collision than at the beginning; this difference would be proof of the existence of extra dimensions.

The validity of string theory could also be supported by astronomical observations, for example, through the analysis of the temperature variations of the radiation emitted just after the Big Bang – known as the cosmic microwave background (CMB).(1) The Planck satellite, which should be launched during 2007, will measure the temperature distribution of

(1) The cosmic microwave radiation is the first light which was propagated freely in the Universe, 300 000 to 400 000 years after the Big Bang. See RDT information, special number Science and Memory, April 2005.



The billions of stars in a galaxy are no more than the visible tip of the iceberg as far as space is concerned. Galaxies are largely composed of invisible black matter. Shown here is the Messier 83 galaxy, south of the Hydra constellation. Its distance is estimated at around 15 million light years. ©ESO

the CMB with an unequalled resolution – and there is a chance that it will find a footprint confirming the validity of string theory.

R.D.: Moreover, during the last five years, cosmological observations have shown that the nature of only 4% of the energy content of the Universe is known. Thus 96% remains unexplained, of which a quarter could be invisible particles that are defined as 'dark matter'. But we know nothing about the nature of these particles. A new instrument, such as the LHC, could make it possible to learn more.

How could the Universe be populated by so much dark matter that we have never seen?

R.D.: In a general way, the known matter in the Universe interacts by the means of the fundamental forces. Thus, the light emitted by a celestial object is due to electromagnetic interactions and these are what make it visible. But there could be particles that only interact a little, or not at all. Indeed, there is no reason for everything to interact with everything else in the Universe. Thanks to string theory, we can predict the existence of some particles that do not interact via the electromagnetic or nuclear forces. However, since they exist, they are carrying energy, which implies that they have mass and thus are subject to the universal laws of gravity. This characteristic is the first step in identifying 'candidate' particles that might qualify as dark matter. But string theory goes further by predicting that the best placed dark energy candidates will be the lightest particles with supersymmetric characteristics.

Why should these dark matter particles be the lightest – and what does the concept of supersymmetry mean?

R.D.: The extreme lightness of such particles means that they have reached a limit which prevents them from decaying. Thus they are very stable and could be particularly widespread throughout the Universe.

To explain supersymmetry, we start with the observation that, in nature, there seem to be two categories. On the one hand, we have what we call matter and, on the other hand, the forces that act within matter, for instance electric forces. Usually, we consider these two categories separately, that is to say, not symmetrically. String theory tells us to bridge this separation by introducing the concept of supersymmetry. This latter rests on the assumption that there is a symmetry connecting matter and force, like the image of an object in a mirror. This assumption allows us to deduce the existence of new particles likely to constitute the dark matter in the Universe. It is a very important idea, but, at present, it remains just a theory. Does it explain the reality of nature? To date, no experimental proof of the supersymmetry concept is yet forthcoming.

Our human perception of the Universe is traditionally based on three-dimensional space (height, width, depth) to which is added the fourth dimension of time. However, string theory requires more than three dimensions in space. The idea of spatial dimensions that we cannot perceive is quite difficult to grasp…

B.G.: Until now, most physical theories assume the three-dimensionality of the Universe. String theory does not make such an assumption but, by purely mathematical reasoning, predicts that there should be more than three. Why are we unable to perceive these extra dimensions? They could be imperceptible because they are somehow 'folded in on themselves'. So, like an ant on a wire, we can only move along the wire, we are unaware of the dimension related to its thickness. In contrast, another possibility could be that these extra dimensions are very large but light for instance could not propagate through them: light would be trapped in our three-dimensional Universe, preventing us from seeing the extra dimensions.

To come back to the quest for a quantum gravity theory, can we imagine that it will unify the four fundamental forces of nature, namely the electromagnetic force, the strong and weak nuclear interactions of quantum mechanics and the gravitational force of general relativity?

B.G.: This is not a necessary consequence to unify all the forces to build a theory of quantum gravity but it is one of string theory's consequences. However, in other approaches merging gravity and quantum mechanics – string theory is not the only one. Only experimental data will solve this question.

R.D.: It should nevertheless be stressed that some relevant information already exists. The fundamental forces vary enormously in their properties and their amplitudes. In atoms, the nuclear forces are very strong, whereas gravity is very weak. However, during experiments, if we increase the particle energy more and more, the properties of the different forces become increasingly similar and end up acquiring about the same amplitude. Hence, at high energies, they naturally tend to unify.

B.G.: These high-energy conditions are probably those that prevailed at the beginning of the Universe and, if we had existed then, we would probably have perceived only one master force instead of four different ones.

To the question "Was there something before the Big Bang", Professor Stephen Hawking answers, "There is nothing to the north of the North Pole "…

R.D.: This question is equivalent to wondering how time and space could start with the Big Bang. As one approaches the Big Bang, the concepts of time and space stop making sense, as does the concept of latitude when one arrives at the North Pole.

But then how do time and space appear?

R.D.: According to certain theories, space could emerge from nothing, and a similar phenomenon probably occurs for time.

How can space and time emerge from nothing?


View of String 2, the test bed for the LHC, the future collider currently being installed at CERN (Geneva) to permit the production of super symmetrical products. The inset shows the first LHC superconducting magnet being lowered into the accelerator tunnel, in May 2005. © CERN

R.D.: Take the example of temperature. In a room you have gas made of molecules, each of these molecules has energy and the average energy of the gas is what is called the temperature. When there is only a single molecule, the notion of temperature cannot be defined. Hence temperature, pressure and many other concepts only emerge if you have many particles. Consequently, some of the fundamental laws of physics only emerge beyond a certain limit. It could be the same case for space and time.

B.G.: One could also imagine a pre-Big Bang, namely a Universe in existence before the Big Bang, which could have collapsed in on itself into a fundamental state from where space and time would emerge.

A black hole results from the collapse of a massive star. Like the Big Bang, general relativity predicts that all the matter in a star collapses into a point of infinite density. What does string theory tell us about this subject?

R.D.: The funny thing with black holes is that they are a kind of mini-version of the Big Bang, with similarities, but in reverse order. The matter falls into a black hole whereas it emerges from the Big Bang. Some astrophysicists, in particular Stephen Hawking, showed that a black hole is not black but radiates particles. It evaporates. His calculations were an approximation but string theory makes it possible from now on to formulate them in an exact way, by including all the quantum effects at small scales.

B.G.: If some microscopic black holes could be produced in the LHC, it would be possible to examine the products of their evaporation and to observe them decay.

R. D.: And the energy released by this decay would be such that any particle could result, thus giving us a chance to detect the famous supersymmetric particles predicted by string theory. ■

BRIAN GREENE

Brian Greene is Professor of physics and mathematics at Columbia University (New York) where he is Co-Director of the Institute for Strings, Cosmology and Astroparticle Physics and leads a research programme on the implications of string theory for the universe. In 2000, he won the Aventis Prize for his popular book on string theory, entitled *The Elegant Universe*. His second book, *The Fabric of the Cosmos: Space, Time and the Texture of Reality* is about space and time and lasted 25 weeks on *The New York Times* bestsellers list. *The Washington Post* describes him as "the single best explainer of abstruse concepts in the world today".

ROBBERT DIJKGRAAF

Robbert Dijkgraaf is Professor of mathematical physics at Amsterdam University where his research group is working on string theory, quantum gravity and the interface between mathematics and particles physics. Among his many awards, he is holder of the Spinoza Prize from the Dutch Physical Society. He is a Member of the Royal Netherlands Academy of Arts and *Sciences* and the Royal Holland Society of Sciences and Humanities. Interested in scientific communication, he writes regularly for the Dutch Press, including as a columnist for *NRC Handelsblad* and *Folia*.