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Newly devised test may confirm strings as fundamental constituent of matter, energy

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Experimental verification would mean more spatial dimensions exist

Santa Barbara, Calif.--According to string theory, all the different particles that constitute physical reality are made of the same thing--tiny looped strings whose different vibrations give rise to the different fundamental particles that make up everything we know. Whether this theory correctly portrays fundamental reality is one of the biggest questions facing physicists.

In the June on-line Journal of High Energy Physics (JHEP), three theoretical physicists propose the most viable test to date for determining whether string theory is on the right track. The effect that they describe and that could be discovered by LIGO (Laser Interferometer Gravitational-Wave Observatory), a facility for detecting gravitational waves that is just becoming operational, could provide support for string theory within two years.

When physicists look at fundamental particles--electrons, quarks, and photons--with the best magnifiers available (huge particle accelerators such as those at Fermi Lab in Illinois or CERN in Switzerland), the particles' structures appear point-like. In order to see directly whether that point-like structure is really a looped string, physicists would have to figure out how to magnify particles 15 orders of magnitude more than the 13 orders of magnitude afforded by today's best magnifying techniques--a feat unlikely to occur ever.

In their paper "Cosmic F and D Strings," the three physicists propose looking instead for the gravitational signature of strings left over from the creation of the universe.

The physicists are Joseph Polchinski of the Kavli Institute for Theoretical Physics at the University of California at Santa Barbara (UCSB), Edmund Copeland of Sussex University in England, and Robert Myers of the Perimeter Institute and Waterloo University in Canada.

The international collaboration took place at a semester-long program on "Superstring Cosmology" held last fall at the Kavli Institute for Theoretical Physics (KITP). Located on the UCSB campus and supported principally by the National Science Foundation (NSF), the Kavli Institute brings together physicists worldwide to collaborate on deep scientific questions. According to Polchinski, who is a string theorist, the KITP program that produced the test for string theory was the first sustained effort ever to bring cosmologists and string theorists together to advance the newly emerging field of string cosmology. Two-thirds of the roughly 100 participants were string theorists; and the other third, astrophysicists.

In the mid 1980s Edward Witten, now at the Institute for Advanced Study in Princeton, asked whether miniscule strings produced in the early universe would grow with the universe to a size that would make them visible today. Witten answered his own question negatively by raising three objections to the idea. Because of subsequent developments, all three objections have in turn now been answered, according to Polchinski and his collaborators, who dispelled the last objection and then proposed a way of detecting those strings.

The first objection depends on a property of strings called "tension," which is the mass of a string per unit length.

"One way to characterize that number," said Polchinski, "involves the gravitational effect of the string. If you look at a string end on while a couple of light rays go past it on either side, the light rays will bend towards the string. So light rays that started out parallel to each other will now meet at some angle. The heavier the string, the more those light rays will bend, and the bigger the angle."

When Witten first worked on the problem, string theorists thought that angle had to be one degree. If it were one degree, the satellite COBE (Cosmic Background Explorer) would have detected that imprint in the microwave background radiation, which pervades the universe and which was released when the early universe cooled enough for matter and energy to decouple some 300,000 years after the hot birth of the universe. The maps of the early universe that COBE produced show no such imprint and, furthermore, put an upper limit on that angle of no more than one hundredth of a degree. The satellite WMAP (Wilkinson Microwave Anisotropy Probe) has now reduced it to one thousandth of a degree.

In the mid-1990s string theory underwent profound developments. One of the consequences of those developments was the realization that the tension of the string and therefore its gravitational effect could be much less than had been thought when Witten made his initial calculation of the angle of separation between light rays affected gravitationally by a string.

Henry Tye of Cornell and his collaborators showed that in some string theory models the angle of separation would be between a thousandth of a degree and a billionth of a degree--far too small for COBE to have detected.

Tye and collaborators also demolished the second objection to cosmic strings having to do with "Inflation," which can be thought of as an intensification of the explosion and rapid expansion of the early universe following rapidly on the heels of the universe's genesis in the "Big Bang." Witten back in the '80s had argued that the strings produced by the Big Bang would be both heavy enough and produced so early that Inflation would have diluted them beyond visibility.

String theory presupposes nine or 10 spatial dimensions, that is six or seven more spatial dimensions than have heretofore been assumed to exist in addition to the one dimension of time. Some of the "extra" dimensions are thought to be curled up or compactified and therefore exceedingly small; and some, to be larger, perhaps infinite.

In his attempts to understand Inflation in terms of string theory, Tye and collaborators envisioned our reality as contained in a three-dimensional "brane" sitting in higher dimensional space.

Branes, a key conceptual breakthrough discovered by Polchinski in 1995, are essential structures in string theory in addition to strings. Instead of being only one-dimensional like strings, branes can have any dimensionality, including one. One-dimensional branes are called "D1 branes or D strings." So there are essentially two types of strings-- the heterotic string or "F" (for "fundamental") string, which physicists knew about prior to 1995, and the "D string," or one-dimensional brane.

Tye and collaborators explained Inflation in terms of a brane and an anti-brane separating from each other and then attracting back together and annihilating. So a brane and an anti-brane existing in the extra dimensions would thereby provide the energy responsible for Inflation. Everything existing afterwards--our universe--is the product of their annihilation. And, according to the Tye models, at the end of Inflation, when brane and anti-brane annihilate, not only does their annihilation produce heat and light, but also long closed strings that could grow with the expansion of the universe.

At the outset of the KITP program in fall 2003, the only remaining objection to cosmic strings was what Polchinski calls summarily "the stability argument," first made by Witten back in the '80s. If, on the one hand, the post-Inflation strings were charged, then they would pull back together and collapse before they could grow to any great size. If the strings weren't charged, then they would tend to break into pieces. Either way--collapsing or breaking--the strings couldn't survive until today.

Copeland, one of the JHEP paper's authors, went to a talk at the KITP by Stanford string theorist Eva Silverstein, who was interested in networking F and D strings--hooking them together to form something analogous to a wire mesh or screen. After the talk, Copeland wondered aloud to Polchinski whether Silverstein (who was thinking string theory mathematics, not cosmology) was inadvertently describing a mechanism for the dark matter--that as yet unidentified, non-radiating component of the universe which must exist in much greater abundance than all the ordinary "baryonic" matter of which we are aware.

Polchinski and Copeland worked out why Silverstein's scenario could not pertain to dark matter, but the engagement with that question got Polchinski to thinking about the old instability argument against the existence of cosmic strings in terms of Tye's brane-antibrane Inflation, particularly as worked out in detail by six physicists in a 2003 paper, "Towards Inflation in String Theory."

Using that model, Polchinski, Copeland, and Myers calculated the decay rates for cosmic strings and discovered how slow the rates could be--so slow in fact that the strings would survive to the present day. By "survive" they mean not just detecting the gravitational footprint left long ago in the cosmic microwave background and "seen" by looking back in time, but actually seeing the gravitational effects of cosmic strings existing if not now, then billions of years after the genesis of the universe.

Polchinski said their calculations showed that both F and D cosmic strings could exist and that the JHEP article explains how to distinguish the signature of one from the other. He also pointed out that Gia Dvali (New York University) and Alexander Vilenkin (Tufts University) have independently made the same point about cosmic D strings in March in another on-line publication, the Journal of Cosmology and Astroparticle Physics (JCAP).

Finally and most importantly, the JHEP authors show, said Polchinski, "how we can see cosmic strings. They are dark, but because they are massive and moving pretty fast, they tend to emit a lot of gravitational waves."

During the "Superstring Cosmology" program at the KITP, Alessandra Buonanno (Institut d'Astrolophysique de Paris) provided an overview of the possible gravitational wave signatures from the early universe. "When she gave the talk," said Polchinski, "I didn't pay careful attention because I wasn't thinking about that, but later I went back to her talk in the KITP online series and started clicking through and got to where she talked about gravitational waves from cosmic strings. She had these curves which were quite amazing."

The large-scale, long-term experiment to detect gravitational waves has three stages, LIGO I and II and the satellite LISA, with each successive stage affording a markedly higher degree of sensitivity. Most of the gravitational signatures of cosmic events are so weak that they will probably only be visible in the later stages of the experiment. But, according to Polchinski, "the gravitational signatures from cosmic strings are remarkable because they are potentially visible even from the early stages of LIGO! That means 'potentially visible' over the next year or two."

Gravitational waves have yet to be directly detected, which is the mission of the LIGO and LISA experiments. So in addition to the possibility of confirming string theory, the JHEP paper offers a better target for initial LIGO detection of gravitational waves than any other from cosmic events.

Identifying the gravitational signature of cosmic strings is the work of Vilenkin and Thibault Damour (Institut des Hautes Etudes Scientifiques, France). They figured out that when cosmic strings oscillate, every once in a while, they crack like a whip. "It's surprising," said Polchinski, "but when you write out the equations for an oscillating string, a little piece of the string snaps and moves very fast. Basically, the tip will move at the speed of light. When a string cracks like this, it emits a cone of gravitational waves, which is a remarkably intense and distinctive signal, which LIGO can detect."

Polchinski said that the biggest question mark in the whole argument has to do with the stability of the strings over billions of years. But, he added, "There has been a fair amount of discussion about the signature of string theory in cosmology, this is by far the most likely. What excites me most is how much we could learn about string theory if LIGO were to detect the signal from cosmic strings."

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