Listening for Gravitational Echoes of the Universe's Birth

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This is an aerial view of the LIGO facility in Livingston, La. Credit: LIGO, courtesy of California Institute of Technology

(PhysOrg.com) -- An investigation by a major scientific group has advanced understanding of the early evolution of the universe.

An investigation by the LIGO (Laser Interferometer Gravitational-Wave Observatory) Scientific Collaboration and the Virgo Collaboration has significantly advanced our understanding the early evolution of the universe.

Analysis of data taken over a two-year period, from 2005 to 2007, has set the most stringent limits yet on the amount of gravitational waves that could have come from the Big Bang in the gravitational wave frequency band where LIGO can observe. In doing so, the gravitational-wave scientists have put new constraints on the details of how the universe looked in its earliest moments.

Much like it produced the cosmic microwave background, the Big Bang is believed to have created a flood of gravitational waves—ripples in the fabric of space and time—that still fill the universe and carry information about the universe as it was immediately after the Big Bang. These waves would be observed as the "stochastic background," analogous to a superposition of many waves of different sizes and directions on the surface of a pond. The amplitude of this background is directly related to the parameters that govern the behavior of the universe during the first minute after the Big Bang.

Earlier measurements of the cosmic microwave background have placed the most stringent upper limits of the stochastic gravitational wave background at very large distance scales and low frequencies. The new measurements by LIGO directly probe the gravitational wave background in the first minute of its existence, at time scales much shorter than accessible by the cosmic microwave background.

The research, which appears in the August 20 issue of the journal *Nature,* also constrains models of cosmic strings, objects that are proposed to have been left over from the beginning of the universe and subsequently stretched to enormous lengths by the universe's expansion; the strings, some cosmologists say, can form loops that produce gravitational waves as they oscillate, decay, and eventually disappear.

Gravitational waves carry with them information about their violent origins and about the nature of gravity that cannot be obtained by conventional astronomical tools. The existence of the waves was predicted by Albert Einstein in 1916 in his general theory of relativity. The LIGO and GEO instruments have been actively searching for the waves since 2002; the Virgo interferometer joined the search in 2007.

The authors of the new paper report that the stochastic background of gravitational waves has not yet been discovered. But the nondiscovery of the background described in the Nature paper already offers its own brand of insight into the universe's earliest history.

The analysis used data collected from the LIGO interferometers, a 2 km and a 4 km detector in Hanford, Washington, and a 4 km instrument in Livingston, Louisiana. Each of the L-shaped interferometers uses a laser split into two beams that travel back and forth down long interferometer arms. The two beams are used to monitor the difference between the two interferometer arm lengths.

According to the general theory of relativity, one interferometer arm is slightly stretched while the other is slightly compressed when a gravitational wave passes by.

The interferometer is constructed in such a way that it can detect a change of less than a thousandth the diameter of an atomic nucleus in the lengths of the arms relative to each other.

Because of this extraordinary sensitivity, the instruments can now test some models of the evolution of the early universe that are expected to produce the stochastic background.

"Since we have not observed the stochastic background, some of these early-universe models that predict a relatively large stochastic background have been ruled out," says Vuk Mandic, assistant professor at the University of Minnesota.

"We now know a bit more about parameters that describe the evolution of the universe when it was less than one minute old," Mandic adds. "We also know that if cosmic strings or superstrings exist, their properties must conform with the measurements we made—that is, their properties, such as string tension, are more constrained than before."

This is interesting, he says, "because such strings could also be so-called fundamental strings, appearing in string-theory models. So our measurement also offers a way of probing string-theory models, which is very rare today."

"This result was one of the long-lasting milestones that LIGO was designed to achieve," Mandic says. Once it goes online in 2014, Advanced LIGO, which will utilize the infrastructure of the LIGO observatories and be 10 times more sensitive than the current instrument, will allow scientists to detect cataclysmic events such as black-hole and neutron-star collisions at 10-times-greater distances.

"Advanced LIGO will go a long way in probing early universe models, cosmic-string models, and other models of the stochastic background. We can think of the current result as a hint of what is to come," he adds.

"With Advanced LIGO, a major upgrade to our instruments, we will be sensitive to sources of extragalactic gravitational waves in a volume of the universe 1,000 times larger than we can see at the present time. This will mean that our sensitivity to gravitational waves from the Big Bang will be improved by orders of magnitude," says Jay Marx of the California Institute of Technology, LIGO's executive director.

"Gravitational waves are the only way to directly probe the universe at the moment of its birth; they're absolutely unique in that regard. We simply can't get this information from any other type of astronomy. This is what makes this result in particular, and gravitational-wave astronomy in general, so exciting," says David Reitze, a professor of physics at the University of Florida and spokesperson for the LIGO Scientific Collaboration.

"The scientists of the LIGO Scientific Collaboration and the Virgo Collaboration have joined their efforts to make the best use of their instruments. Combining simultaneous data from the LIGO and Virgo interferometers gives information on gravitational-wave sources not accessible by other means. It is very suggestive that the first result of this alliance makes use of the unique feature of gravitational waves being able to probe the very early universe. This is very promising for the future," says Francesco Fidecaro, a professor of physics with the University of Pisa and the Istituto Nazionale di Fisica Nucleare, and spokesperson for the Virgo Collaboration.

Maria Alessandra Papa, senior scientist at the Max Planck Institute for Gravitational Physics and the head of the LSC overall data analysis effort adds, "Hundreds of scientists work very hard to produce fundamental results like this one: the instrument scientists who design, commission and operate the detectors, the teams who prepare the data for the astrophysical searches and the data analysts who develop and implement sensitive techniques to look for these very weak and elusive signals in the data."

The LIGO project, which is funded by the National Science Foundation (NSF), was designed and is operated by Caltech and the Massachusetts Institute of Technology for the purpose of detecting gravitational waves, and for the development of gravitational-wave observations as an astronomical tool.

Research is carried out by the LIGO Scientific Collaboration, a group of 700 scientists at universities around the United States and in 11 foreign countries. The LIGO Scientific Collaboration interferometer network includes the LIGO interferometers and the GEO600 interferometer, which is located near Hannover, Germany, and designed and operated by scientists from the Max Planck Institute for Gravitational Physics, along with partners in the United Kingdom funded by the Science and

Technology Facilities Council (STFC).

The Virgo Collaboration designed and constructed the 3 km long Virgo interferometer located in Cascina, Italy, funded by the Centre National de la Recherche Scientifique (France) and by the Istituto Nazionale di Fisica Nucleare (Italy). The Virgo Collaboration consists of 200 scientists from five Europe countries and operates the Virgo detector. Support for the operation comes from the Dutch-French-Italian European Gravitational Observatory Consortium. The LIGO Scientific Collaboration and Virgo work together to jointly analyze data from the LIGO, Virgo, and GEO interferometers.

The next major milestone for LIGO is the Advanced LIGO Project, slated to begin operation in 2014. Advanced LIGO will incorporate advanced designs and technologies that have been developed by the LIGO Scientific Collaboration. It is supported by the NSF, with additional contributions from the U.K.'s STFC and Germany's Max Planck Society.

More information: The paper is entitled "An Upper Limit on the Amplitude of Stochastic Gravitational-Wave Background of Cosmological Origin." www.nature.com/nature/journal/ … ull/nature08278.html

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