Theoretical interpretations of the pulsar timing data recently released by NANOGrav

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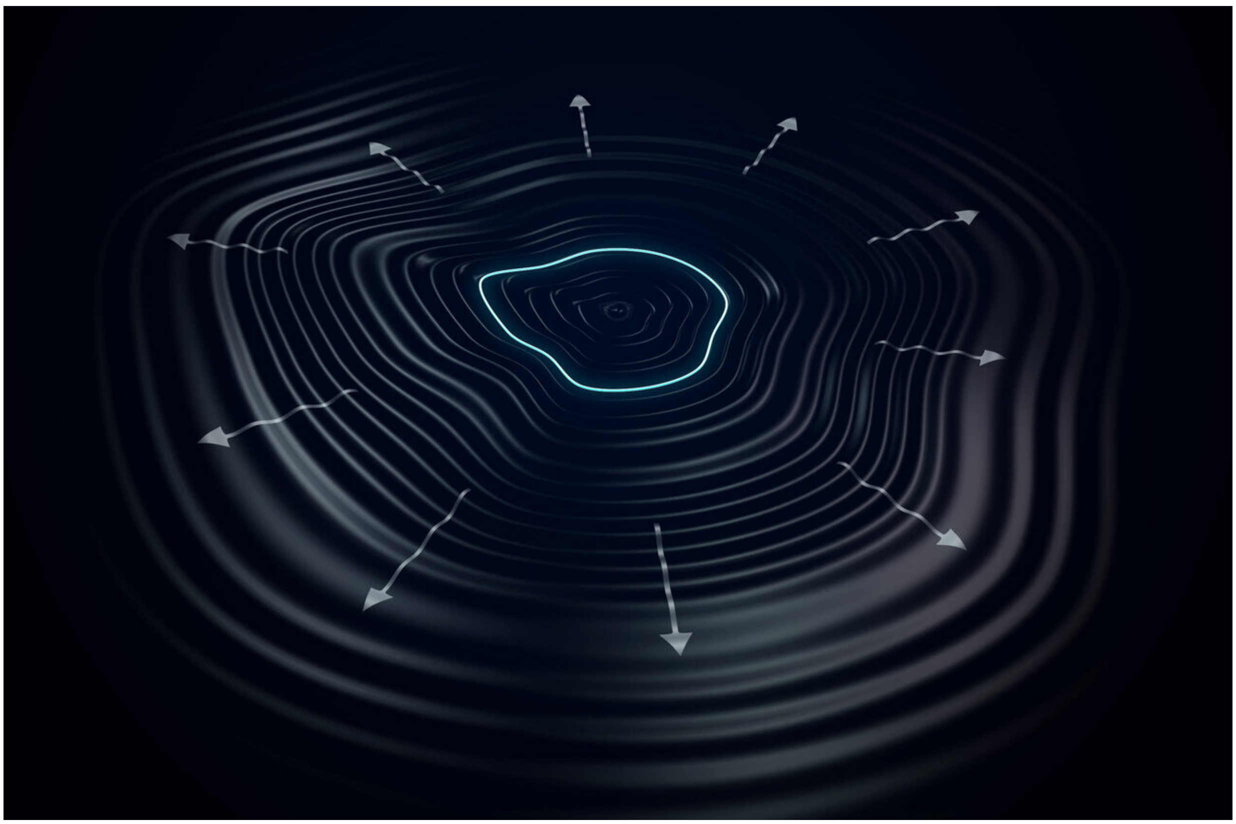

Artistic representation of a cosmic-string loop emitting gravitational waves. Credit: Daniel Dominguez from CERN's Education, Communications & Outreach (ECO) Department.

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) is a gravitational-wave detector that monitors areas in the vicinity of Earth using a network of pulsars (i.e., clock-like stars). At the end of 2020, the NANOGrav collaboration gathered evidence of fluctuations in the timing data of 45 pulsars, which could be compatible with a stochastic gravitational wave background (SGWB) signal at nanohertz frequencies.

These gravitational waves could potentially be linked to the mergers of extremely massive black holes. Teams of theoretical physicists worldwide, however, have provided alternative explanations for the gravitational waves observed by NANOGrav. Some groups have suggested that they could have been produced by superdense filaments known as cosmic strings, while others hypothesized that they could have been generated during the birth of primordial black holes.

A cosmic string interpretation of the NANOGrav data

John Ellis and Marek Lewicki, two researchers at King's College London and the University of Warsaw, recently offered a cosmic string theoretical interpretation of the new NANOGrav data. They showed that the SGWB signal that NANOGrav may have observed could be produced by a network of cosmic strings born in the early universe. The researchers theorized that this network would evolve as the universe expands, producing closed loops when strings collide. These loops would then slowly decay into gravitational waves, resulting in the signal detected by NANOGrav.

"We showed that cosmic strings provide a very good fit to the NANOGrav signal, slightly better than the possible alternative source of supermassive black hole binaries," Ellis and Lewicki said. "Moreover, we showed that our hypothesis will be straightforward to test in future gravitational wave observatories such as LISA."

"Our research is based on years of work by many groups that made possible accurate calculations of the gravitational wave signal produced by cosmic strings," Ellis and Lewicki told Phys.org. "We sprang into action as soon as we learned of the promising new data from the NANOGrav collaboration, to check how good a candidate a network of cosmic strings would be for explaining the data."

Ellis and Lewicki's paper points out that the expansion history of the universe is also encoded in the signal. This is because the network of cosmic strings they describe would emit a signal throughout the history of the universe and all the features in the universe's expansion would leave a matching imprint on the signal's spectrum that could then be probed by future detectors.

"Thanks to the strength of the signal needed to explain the NANOGrav data, this would allow the history of the universe to be probed back to times much earlier than previously thought, warranting further study," Ellis and Lewicki said. "We are currently working towards AION and AEDGE, which are new proposed experiments that could in the future probe a different part of the history of the universe than NANOGrav or LISA, and potentially test our interpretation of the NANOGrav data."

The NANOGrav signal as the first evidence of cosmic strings

In parallel to the work by Ellis and Lewicki, researchers at Max-Planck-Institut für Kernphysik (MPIK) and CERN also tried to theoretically demonstrate that gravitational waves from cosmic strings are a well-motivated and perfectly viable explanation for the pulsar timing signal detected by NANOGrav. Their paper, published in *Physical Review Letters*, builds on a number of previous studies in the field of gravitational-wave astronomy.

"Since the ground-breaking detection of gravitational waves by LIGO in 2015, the field of gravitational-wave astronomy has continued to make progress at an impressive pace," Kai Schmitz from CERN, one of the authors of the paper, told Phys.org. "Thus far, all observed signals were caused by astrophysical events such as the mergers of binary black holes. These events are called 'transient' and only lead to short-lasting signals in gravitational-wave detectors. The next big step in gravitational-wave astronomy is therefore going to be the detection of a stochastic 'background' of gravitational waves, a signal that is constantly present, reaching us from all directions in space."

The detection of 'background' gravitational signals could be associated with a broader variety of astrophysical and cosmological phenomena, ranging from binary mergers to events that took place in the early universe. Remarkably, such a SGWB signal could also be the gravitational-wave equivalent of the cosmic microwave background (CMB) signal, which is essentially the afterglow of the Big Bang in electromagnetic radiation and at microwave frequencies.

"As particle physicists, we are particularly interested in the primordial contributions to the SGWB, which promise to encode a wealth of information on the dynamics of the early universe and hence particle physics at the highest energies," Schmitz said. "Possible sources of primordial gravitational waves could be cosmic inflation, phase transitions in the vacuum structure of the early universe and cosmic strings. In our previous projects, we had already explored all three of these possibilities."

In their recent study, Schmitz and his MPIK colleagues Simone Blasi and Vedran Brdar hypothesized that the pulsar timing data collected by NANOGrav might be the first evidence of cosmic strings. Cosmic strings are theorized to be the remnants of phase transitions at extremely high energies, possibly close to the energy scale of grand unification (i.e., the energies at which all the subatomic forces of nature are predicted to unify in a common force).

"In this case, the phase transition giving birth to cosmic strings is unlikely to lead to an observable signal in gravitational waves itself, either because it simply does not produce any appreciable signal or because the signal is located at high, unobservable frequencies," Schmitz said. "Cosmic strings, however, the remnants of the phase transition, have a chance to produce a large signal in gravitational waves that, if detected, can tell us about the symmetries and forces that governed the universe during the first moments of its existence."

In the past, physicists have proposed a number of theoretical models that speculate on what types of new physics might give rise to a network of cosmic strings in the early universe. In some of their past studies, Schmitz, Blasi and Brdar specifically focused on the idea that cosmic strings might be related to the origin of neutrino masses and the cosmic asymmetry between matter and antimatter.

"This connection between gravitational waves, cosmic strings and the so-called seesaw mechanism, the most studied realization of neutrino mass generation, was explored in numerous studies, both by us and other teams," Schmitz said. "Cosmic strings of this type are referred to as 'cosmic B-L strings," as they result from a cosmological phase transition that leads to the violation of B-L (B minus L) symmetry; where B-L stands for the difference of baryon (B) and lepton (L) number. B-L symmetry plays an important role in the seesaw mechanism; only the "breaking" of this symmetry in the early universe paves the way for a physical state of the universe in which neutrinos can acquire mass via the seesaw mechanism."

Schmitz and his colleagues have already theorized about gravitational waves that could arise from cosmic B-L strings in a paper published in

2020. In this previous work, they specifically focused on the gravitational-wave spectrum at higher frequencies, exploring the possibility of probing special corners of parameter space that are relevant from the perspective of the seesaw mechanism.

"When we first heard about the new NANOGrav result, we were fully prepared to compare our predictions for a cosmic-string-induced gravitational-wave signal to the signal in the NANOGrav data," Schmitz said. "We thus immediately began to compute the gravitational-wave spectrum from cosmic strings in the nanohertz frequency range. Unlike our analysis in April 2020, we no longer focused on cosmic B-L strings, but considered cosmic strings in a more general sense, remaining agnostic about the details of their origin at very high energies."

In their recent study, Schmitz, Blasi and Brdar wanted to show that the signal observed by NANOGrav could reflect the gravitational waves produced by cosmic strings. Moreover, they tried to map out the entire viable region in the cosmic-string parameter space that would allow one to fit the data.

"At present, it is important to remain cautious, as it is not even clear yet whether NANOGrav has really detected a gravitational-wave background," Schmitz said. "To this end, it is first necessary to detect a specific correlation pattern among the timing residuals of individual pulsars. This pattern can be depicted as a graph showing the correlation among pairs of pulsars as a function of the angle separating two pulsars in the sky; this graph is the famous Hellings-Downs curve."

NANOGrav monitors an array of pulsars in our galactic neighborhood to search for gravitational waves at nanohertz frequencies. Credit: NANOGrav.

In order to confirm that the signal detected by NANOGrav derives from gravitational waves, physicists would first need to show that it conforms to the Hellings-Downs curve. While the data appears to be fairly aligned with this interpretation, researchers are yet to gather sufficient evidence of the Helling-Downs pattern emerging in the data. Ongoing and future studies, however, could ultimately ascertain the validity of the NANOGrav pulsar timing signal and measure some of its properties with better precision. Measuring the NANOGrav signal's properties (e.g., whether it rises/falls as a function of frequency and, if so, how fast it rises/falls) could help to determine its possible sources.

"All we can say is that, at present, gravitational waves from cosmic strings are a perfectly viable explanation of the signal," Schmitz said. "Cosmic strings result in the right amplitude A of the signal; they result in a spectral index gamma that is perfectly consistent with the NANOGrav bounds on this parameter; and the predicted gamma values are even slightly (but only by a tad bit) better in agreement with the data than the value gamma = 13/3 predicted by supermassive black hole binaries."

Overall, the study carried out by Schmitz, Blasi and Brdar theoretically demonstrates that cosmic strings could be a viable explanation of the NANOGrav signal. Moreover, the researchers showed that the cosmic-string interpretation works for a large range of the two cosmic-string parameters that they focused on in their paper: the cosmic-string tension Gmu and the cosmic-string loop size alpha.

"This makes the cosmic-string interpretation flexible and opens up many possibilities regarding the possible origin of the cosmic strings," Schmitz explained. "Large loops with a small tension can explain the signal, smaller loops with a somewhat larger tension can explain the signal, etc."

In addition to theoretically demonstrating that the NANOGrav signal could reflect cosmic strings, the researchers showed that future gravitational-wave experiments at higher frequencies will probe a large viable parameter space. This finding suggests that gravitational waves from cosmic strings may be an ideal benchmark for multifrequency gravitational-wave astronomy.

"Unlike many other explanations of the NANOGrav signal, we predict that cosmic strings will also lead to a signal that will be observed in space-based and next-generation ground-based experiments," Schmitz said. "This aspect of our interpretation highlights the complementarity of these measurements at low and high frequencies. A positive detection at high frequencies will especially allow one to reconstruct the expansion history of the early universe."

The parameter Gmu, characterizing the cosmic-string tension, or energy per unit length, can be translated into an estimate of the energy scale at which cosmic strings have supposedly formed in the early universe. The Gmu values that Schmitz and his colleagues found in their analysis point to an energy scale in the range from 10^{14} to 10^{16} GeV.

"These are typical values that one also encounters in grand unified theories (GUTs) that describe the unification of subatomic forces at very high energies," Schmitz explained.

"Our results are therefore consistent with the idea of grand unification and the breaking of certain symmetries in the early universe that result in the creation of a network of cosmic strings."

While the theoretical analyzes carried out by this team of researchers are very insightful, it is important to note that models of the gravitational-wave signal that would be produced from cosmic strings are associated with some theoretical uncertainties. For instance, two of the most widely used approaches to study cosmic string dynamics in large-scale computer simulations, namely the "Nambu-Goto strings" and "Abelian Higgs strings" approaches, do not always lead to the same results.

"In our work, we make use of simulations of Nambu-Goto strings," Schmitz added. "In the long term, it would be interesting to resolve the discrepancy between these two approaches, which, however, is a very challenging task. In the meantime, we therefore plan to proceed in smaller steps and successively improve on the Nambu-Goto description of cosmic strings."

In the Nambu-Goto approximation, cosmic strings are more or less featureless, as they are described as one-dimensional objects that carry a certain amount of energy per unit length.

This representation might not actually reflect the properties of cosmic strings in real scenarios.

"Cosmic strings may actually carry an electric current, they may lose energy via the emission of elementary particles in addition to the emission of gravitational waves, etc.," Schmitz said. "In our next studies, we therefore plan to account for these refinements step by step and investigate how these more sophisticated aspects may manifest themselves in the gravitational-wave spectrum. At the same time, we do not believe that these refinements will overturn our cosmic-string interpretation of the NANOGrav signal."

The NANOGrav data as an indication of primordial black holes

Some researchers have also come up with explanations for the NANOGrav data that do not view the signal in the context of cosmic strings. For instance, a team at Université de Genève suggested that such a SGWB signal could also be generated by the formation of primordial black holes from the perturbations generated as the universe expanded.

"We provided a possible interpretation of the common-spectrum signal, as induced by gravitational waves generated in the early universe in connection with the birth of primordial black holes, which are black holes formed at early epochs during the evolution of the universe," Antonio Riotto, Valerio De Luca and Gabriele Franciolini, the three researchers who carried out the study, told Phys.org via email. "Primordial black holes with masses not far from the typical mass of the asteroids may comprise the totality of the dark matter in the universe and, their formation process leaves behind a stochastic background of gravitational waves that explain the NanoGrav data."

According to Riotto, De Luca and Franciolini, the idea that all the dark matter in the universe is made of primordial black holes and the fact that their formation should leave behind an SGWB signal similar to that detected by NANOGrav might seem unrelated, yet they could be connected in interesting ways. For instance, if primordial black holes made up the whole of dark matter in the universe, it would not be necessary to come up with speculative explanations to describe or explain the existence of dark matter, as it would actually be composed of 'ordinary' matter, which physicists are already familiar with.

"Indeed, if the dark matter is made of primordial black holes, one would not need to invoke some speculative explanations to explain the dark matter: Primordial black holes are, in fact, made of the same ordinary matter we know," the researchers explained. "Our study provides an economical explanation of the signal detected by the NANOGrav collaboration with an elegant connection to the dark matter quest, which could be further investigated with the help of future gravitational wave experiments like LISA, a space interferometer."

The gravitational wave background signal that De Luca, Franciolini and Riotto predicted would be produced by primordial black holes could soon be probed in other frequency ranges (e.g., around milliHertz frequencies). In their next studies, the researchers thus plan to seek for evidence of the existence of primordial black holes generated in the early universe by analyzing new gravitational wave data in other frequencies.

"In particular, we wish to make predictions for the amount of gravitational waves that will be detected in future experiments, such as LISA or the European Einstein Telescope, an underground detector, will detect," the researchers said.

In the near future, the NANOGrav collaboration will try to confirm the validity of the signal it detected. Meanwhile, theoretical physicists worldwide are still working on numerous interesting theories that could explain the nature of this signal. The papers published by these teams at Max-Planck-Institut für Kernphysik, CERN, King's College London, the University of Warsaw and the Université de Genève offer particularly noteworthy interpretations that could be confirmed or refuted by future studies.

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