Early universe may have been dominated by bobbing waves

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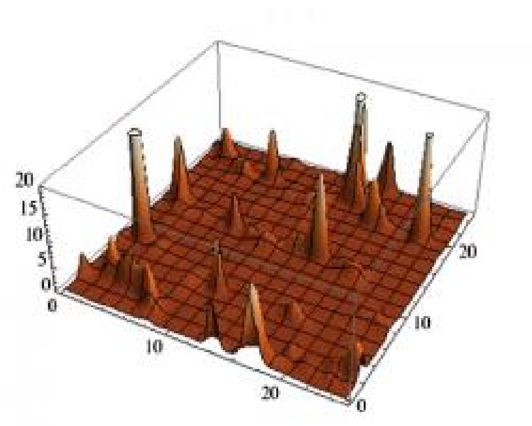

Oscillon simulations show that inflation may have been immediately followed by an oscillon-dominated phase of the early universe. Image credit: Amin, et al. ©2012 American Physical Society

(Phys.org) -- Localized waves that bob up and down without dissipating their energy, called “oscillons,” may have dominated the early universe shortly after inflation. A collaboration of physicists from MIT, Yale University, and Stanford University has discovered that copious amounts of oscillons arise in simulations based on several realistic inflationary models and could have caused novel gravitational effects in the early universe, although it is unclear whether the effects could be directly observed today.

The physicists have published their paper on the possibility of oscillons existing after inflation in a recent issue of *Physical Review Letters*.

As the scientists explain in their paper, oscillons are massive, long-lived excitations of a scalar field that are localized, i.e., they do not dissipate like ripples produced by dropping a pebble in a calm pond. Instead, an oscillon switches between being a hill and a crater, alternately rising above and sinking below the spatially uniform state of the field. In previous experiments, scientists have created oscillons by vertically vibrating a plate with a sufficiently thick layer of granular particles. As long as they're not disturbed, oscillons will continue to move up and down for hundreds of thousands of oscillations.

Oscillon-dominated universe

In the new study, the physicists used simulations to investigate the requirements needed for oscillons to form just after inflation, the period of rapid expansion that occurred from 10^{-36} to 10^{-33} seconds after the Big Bang. In a class of inflationary models that include some string models and supergravity-inspired models, the scientists found that inflation is followed by self-resonance that in turn generates large numbers of oscillons.

"At the end of inflation, the inflaton (the agent responsible for inflation) is oscillating up and down, in sync throughout the universe," coauthor Mustafa Amin at MIT told *Phys.org*, speaking on behalf of his coauthors Richard Easther, Raphael Flauger, and Hal Finkel at Yale University (now at the University of Auckland in New Zealand, the Princeton Institute for Advanced Studies, and Argonne National Laboratory, respectively), and Mark Hertzberg at Stanford University.

"However, this synchronous, homogeneous state cannot be maintained for long," he explained. "It is unstable and quickly fragments into an inhomogeneous, clumpy state. The rapid transfer of energy from the synchronous to the clumpy state is what we call self-resonance. We refer to it as self-resonance because the energy is shuttled from the synchronous, homogeneous state to the clumpy state of the inflation field itself. Interestingly, the mathematics describing this transfer of energy is identical to that describing a child pumping a swing. The child's pumping plays the role of the homogenous, oscillating inflaton whereas the arc of the swing is related to the energy in the clumpy state."

According to the simulations, the oscillons in the early universe would have lived long enough for the universe to grow by a factor of 100 or more, under the assumption that the energy transfer to other particles is suppressed. This period could alter our view of what the universe looked like between the end of inflation and the beginning of radiation domination.

"In many models of particle production after inflation, the inflaton rapidly transfers its energy to a turbulent sea of intermediary particles, which eventually decay into the particles we know and love," Amin said. "Our work shows that, even if the energy transfer to other particles is suppressed, the inflaton can fragment rapidly into localized, coherent structures called oscillons. These oscillons are so ubiquitous that they can dominate the energy density of the universe at that time, which is definitely novel! In terms of altering our basic picture of the early universe, the presence of oscillons increases the clumpiness of the universe on small scales at the end of inflation. Their presence might also alter how the energy from the inflaton is eventually transferred to other particles, and how long it takes to do so. However, to make concrete statements about this and its impact on astrophysics in general, we need to study more realistic models including many more types of particles and gravitational interactions between oscillons."

Amin explained that, although these oscillons would have been much too small to see and very short-lived, the sheer number of them would have enabled them to have a significant impact on the early universe.

"In the class of models we have considered, the oscillons are smaller than the Hubble horizon at the time of production," he said. "The Hubble horizon is a measure of the typical distance light can travel while the universe doubles in size, and can be smaller than the size of an atom. Although small compared to human scales, oscillons are large in the following sense. Oscillons can be thought of as a bag of a large number of inflaton particles. This bag of individual particles can be extremely heavy compared to the heaviest known particles. Although exact numbers of oscillons produced depend on the details of the models used, enough of them can be produced to dominate the energy density of the universe at that time. Their lifetime is a tiny fraction of a second. However, even in this tiny fraction of a second, the universe doubles in size many times over! So as far as this doubling timescale of the universe is concerned, they live extremely long and can have a strong impact on the dynamics within the universe at that time. Regarding whether they move in unison, our simulations show that most of the oscillons do not move much once they are formed (as we mentioned before, they are rather heavy), and the distance between them increases as the universe expands. However, if the gravitational force between them is included, they might clump together to form clusters of oscillons."

Gravitational effects

The physicists calculated that an oscillon-dominated universe would affect the density fluctuations that appeared around that time which later led to the formation of galaxies, stars, and planets. They found that the abundant oscillons would have enhanced the frequency spectrum of the early inhomogeneities, or primordial power spectrum, on very small scales. This enhancement, in turn, could have possibly led to novel gravitational effects at that time.

"When gravity is included, oscillons attract each other, possibly forming bound structures and leading to structure formation not too different than what happens in the contemporary universe (except this happens on a very tiny length scale and very early on in the history of the universe)," Amin said. "In addition, oscillons can merge, fragment or scatter off each other in complex ways when they come close to each other. Another (even more speculative) possibility is that some of these objects could combine and collapse to form primordial black holes, which could then quickly evaporate. All of these possibilities need further work, and will keep us busy."

He added that the presence of oscillons would probably not have had any effect on present-day observations, since oscillons existed on scales much smaller than those that contribute to large-scale structure formation

"It is unclear whether these primordial oscillons will have an effect today," Amin said. "We have not fully understood their implications yet, especially when other particles and gravity is included in the simulations."

Amin and his coauthors are not the only scientists investigating the possible existence of oscillons shortly after inflation. Other researchers, including those at Dartmouth College and the University of Sussex, have also found that oscillons can be produced easily in different early universe processes. But they still have many unanswered questions to investigate.

"Some of us are working on trying to understand how robust these oscillons are when new particles are included in the simulations, which can bleed energy from the oscillons," Amin said. "Some questions we are interested in include: (1) Does the presence of oscillons delay the rate at which the inflation transfers its energy to other particles? (2) How do oscillons clump in the presence of gravity? Do they form clusters? Can they collapse to form primordial black holes? (3) We are also interested in studying what happens during collisions of oscillons. Such interactions will be important to understand the ultimate fate of a collection of oscillons produced in the early universe."

More information: Mustafa A. Amin, et al. "Oscillons after Inflation." *PRL* 108, 241302 (2012). DOI: 10.1103/PhysRevLett.108.241302