Searching for axion dark matter conversion signals in the magnetic fields around neutron stars

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The 100m Robert C. Byrd Green Bank Telescope. Credits: GBT – NRAO/GBO.

According to theoretical predictions, axion dark matter could be converted into radio frequency electromagnetic radiation when it approaches the strong magnetic fields that surround neutron stars. This radio signature, which would be characterized by an ultranarrow spectral peak at a frequency that depends on the mass of the axion dark matter particle in question, could be detected using high-precision astronomical instruments.

Researchers at University of Michigan, University of Illinois at Urbana-Champaign, and other institutes worldwide have recently carried out a search for traces of this axion dark matter conversion in data collected by two powerful telescopes, the Green Bank Telescope (GBT) and the Effelsberg Telescope. Their study was based on their previous research efforts and theoretical predictions, the latest of which is a paper published in 2018.

"The idea proposed in our earlier work and fleshed out in many subsequent publications from throughout the community, is that axion dark matter may convert to narrow-band radio emission in the strong magnetic fields surrounding neutron stars," Benjamin R. Safdi, one of the researchers who carried out the study, told Phys.org. "However, these older works are purely theoretical and involve speculations about how a signal might actually be found in the presence of noisy real-world telescope data. Understandably, there is some skepticism about the feasibility of such a search."

To carry out their search, Safdi and his colleagues first acquired a large body of relevant data collected using radio telescopes. They collected this data using the GBT and the Effelsberg Radio Telescope, two of the biggest radio telescopes in the world located in West Virginia (U.S.) and the Ahr Hills (Germany), respectively.

The researchers pointed these two telescopes toward a variety of targets in the Milky Way and other nearby galaxies. These included neutron stars fairly close to the sun, as well as other regions of the sky that are known to host numerous neutron stars (e.g., toward the center of our galaxy). They then recorded the power measured by the telescope over a range of frequencies. A signal associated with the conversion of axion dark matter would cause excess power in a single frequency channel.

"We then developed and implemented novel and sophisticated data-taking and analysis techniques in order to separate a putative axion signal from confounding backgrounds," Safdi said. "Our search is very much like looking for a needle in a haystack, in the sense that we collect power across millions of different 'frequency channels', but the axion is only expected to contribute excess power in one of these channels, and we do not currently know which one."

A key challenge associated with the search for axion dark matter conversion signatures in radio telescope data is that one may also encounter misleading signals. In fact, terrestrial background (e.g., signals emitted by radio communications, microwave ovens and other equipment on earth) or signals emitted by other astrophysical phenomena could be mistaken for the signals associated with the conversion of axion dark matter in neutron star magnetospheres.

To tackle this challenge and ensure that they did not mistake other signals for axion dark matter conversion radio signatures, Safdi and his colleagues used a series of strategies. For instance, as real axion dark matter conversion signals would only be detected in the region that the telescope is observing at a given time, while terrestrial signals would be observed both in that region and on Earth, they rapidly and continuously switched the telescope from "on source" to "off source" locations while it was pointing toward blank areas in the sky.

"We also implemented sophisticated data analysis techniques to filter and 'learn' the properties of the background from the data itself," Safdi said. "Combining all of these techniques together, we were able to collect and analyze data and conclude, conclusively, that no evidence for axions is present in the data. This was a non-trivial task, but this means that we now have developed and demonstrated an observation and analysis framework that can be used in future studies. This, to me, is the main significance of the paper."

Currently, axions are among the most promising dark matter candidates, thus countless research teams worldwide are trying to detect them. While all searches have been unsuccessful, laboratory axion dark matter searches, such as the Axion Dark Matter Experiment (ADMX) conducted at the University of Washington and other universities worldwide, have so far achieved the most promising results.

The recent study carried out by Safdi and his colleagues suggests that searches based on radio telescope data could be equally valuable in the search for axion dark matter. Interestingly, the search they conducted is based on some of the same fundamental principles behind laboratory experiments known as 'haloscopes'.

Haloscopes are experimental strategies to convert axion dark matter into observable electromagnetic signals using large laboratory magnetic fields. According to theoretical predictions, in the presence of these magnetic fields, axions should transform into electromagnetic radiation, with the extent of this radiation varying according to the size of these fields (i.e., the larger a field is, the larger an axion's electromagnetic signature).

"Cutting-edge laboratory experiments, such as the ADMX experiment, make use of magnetic fields approaching ~10 Tesla (note that the magnetic field strengths in a modern MRI machine are about ~1 Tesla, typically)," Safdi explained. "Neutron stars, on the other hand, can host magnetic fields as large as a 100 billion Tesla. Moreover, the magnetic fields are extended over hundreds of kilometers surrounding the neutron stars, while a laboratory experiment might only maintain these fields over a fraction of a meter."

Essentially, in their search, the researchers were trying to detect the same signals that other teams tried to detect in laboratory experiments. However, while in laboratory experiments the axion-photon conversion process would be rare and the resulting signal would only be detected using sophisticated and well-shielded instruments, in the areas surrounding a neutron star, the same signal would be magnified and violent. So far, most physicists have chosen to conduct dark matter searches based on haloscopes in the lab because electromagnetic signals produced in regions that are far from Earth are still difficult to observe using existing astronomical instruments, as they dim with distance.

"Our work shows that radio observations of neutron stars can compete with laboratory searches and will play an important role in the future toward discovering axion dark matter particles," Safdi said. "I think that this is an important insight because it means that radio telescopes should be part of conversations discussing instrumentation for axion dark matter detection."

The recent work by Safdi and his colleagues suggests that radio telescope observations of neutron stars could be a promising path toward detecting axion dark matter. While they were unable to detect the signals they were searching for, their search allowed the researchers to set constraints on the allowable parameter space of axion dark matter, reaching slightly beyond existing constraints.

Unfortunately, the level of sensitivity of the constraints they set is not high enough for their findings to affect the most renowned quantum chromodynamic (QCD) axion models. Nonetheless, this recent study serves as a proof of principle and could pave the way for similar searches using different data or instruments.

The axion dark matter mass range that the researchers probed so far (i.e., approximately 10 micro-eV) is the range that could ultimately confirm the abundance of dark matter in our universe. For instance, in another study, Safdi and his colleagues Joshua W. Foster and Malte Buschmann estimated that in order to confirm current predictions about the prevalence of dark matter in the universe, the mass of axions should be between 10 and 40 micro-eV.

"This prediction does make assumptions for how, exactly, axion dark matter is produced in the early universe, so it is possible that more complicated production mechanisms are at play that would bring the axion outside of this window, but I think that at present the ~10—40 micro-eV axion window is one of the best-motivated mass ranges for the axion," Safdi said. "While our paper probes axions in this mass range, our results are not quite sensitive enough to probe the best-motivated part of the parameter space, which is the region describing the QCD axion."

If they were validated in experiments, QCD axion theoretical models could shed some light on a number of other natural phenomena that reach beyond the search for dark matter; for instance, explaining why neutrons do not rotate in electric fields. These models, however, predict the occurrence of couplings that are a factor of ~10—100 lower than what the instruments used in the recent study by Safdi and his colleagues were sensitive to. In the future, the researchers would thus ideally like to gather more precise observations that are sensitive to axions in the mass range predicted by QCD models.

"Now that we know that our method works, we are going to acquire significantly more data, with deeper observations across a wider range of frequencies," Safdi said. "We are already planning future observations with Green Bank and Effelsberg that will extend our reach to higher frequencies. To definitively probe the QCD axion, however, we may need to wait for the upcoming Square Kilometer Array (SKA) telescope array, which will be transformational for this search because it will give us orders of magnitude more sensitivity. We are hopeful that searches with SKA will lead to the discovery of the axion or, in the absence of a discovery, play an important role in narrowing down the possible mass range for axions."

More information: Joshua W. Foster et al. Green Bank and Effelsberg Radio Telescope Searches for Axion Dark Matter Conversion in Neutron Star Magnetospheres, *Physical Review Letters* (2020). DOI: 10.1103/PhysRevLett.125.171301

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