Pulsars may make dark matter glow

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The Crab Nebula—a remnant of a supernova explosion which in its center contains a pulsar. The pulsar makes the ordinary matter in the form of gas in the nebula light up. As the researchers have now shown, it may do the same with dark matter in the form of axions, leading to a subtle additional glow that can be measured. Credit: NASA/CXC/ASU/J. Hester et al

The central question in the ongoing hunt for dark matter is: what is it made of? One possible answer is that dark matter consists of particles known as axions. A team of astrophysicists, led by researchers from the universities of Amsterdam and Princeton, has now shown that if dark matter consists of axions, it may reveal itself in the form of a subtle additional glow coming from pulsating stars. Their work is published in the journal *Physical Review Letters*.

Dark matter may be the most sought-for constituent of our universe. Surprisingly, this mysterious form of matter, that physicist and astronomers so far have not been able to detect, is assumed to make up an enormous part of what is out there.

No less than 85% of matter in the universe is suspected to be "dark," presently only noticeable through the gravitational pull it exerts on other astronomical objects. Understandably, scientists want more. They want to really see dark matter—or at the very least, detect its presence directly, not just infer it from gravitational effects. And, of course: they want to know what it is.

Cleaning up two problems

One thing is clear: dark matter cannot be the same type of matter that you and I are made of. If that were to be the case, dark matter would simply behave like ordinary matter—it would form objects like stars, light up, and no longer be "dark." Scientists are therefore looking for something new—a type of particle that nobody has detected yet, and that probably only interacts very weakly with the types of particles that we know, explaining why this constituent of our world so far has remained elusive.

There are plenty of clues for where to look. One popular assumption is that dark matter could be made of axions. This hypothetical type of particle was first introduced in the 1970s to resolve a problem that had nothing to do with dark matter. The separation of positive and negative charges inside the neutron, one of the building blocks of ordinary atoms, turned out to be unexpectedly small. Scientists of course wanted to know why.

It turned out that the presence of a hitherto undetected type of particle, interacting very weakly with the neutron's constituents, could cause exactly such an effect. The later Nobel Prize winner Frank Wilczek came up with a name for the new particle: axion—not just similar to other particle names like proton, neutron, electron and photon, but also inspired by a laundry detergent of the same name. The axion was there to clean up a problem.

In fact, despite never being detected, it might clean up two. Several theories for elementary particles, including string theory, one of the leading candidate theories to unify all forces in nature, appeared to predict that axion-like particles could exist. If axions were indeed out there, could they also constitute part or even all of the missing dark matter? Perhaps, but an additional question that haunted all dark matter research was just as valid for axions: if so, then how can we see them? How does one make something "dark" visible?

Shining a light on dark matter

Fortunately, it seems that for axions there may be a way out of this conundrum. If the theories that predict axions are correct, they are not only expected to be mass-produced in the universe, but some axions could also be converted into light in the presence of strong electromagnetic fields. Once there is light, we can see. Could this be the key to detect axions—and therefore to detect dark matter?

To answer that question, scientists first had to ask themselves where in the universe the strongest known electric and magnetic fields occur. The answer is: in regions surrounding rotating neutron stars also known as pulsars. These pulsars—short for "pulsating stars"—are dense objects, with a mass roughly the same as that of our sun, but a radius that is around 100,000 times smaller, only about 10 km. Being so small, pulsars spin with enormous frequencies, emitting bright narrow beams of radio emission along their axis of rotation. Similar to a lighthouse, the pulsar's beams can sweep across the Earth, making the pulsating star easily observable.

However, the pulsar's enormous spin does more. It turns the neutron star into an extremely strong electromagnet. That, in turn, could mean that pulsars are very efficient axion factories. Every single second an average pulsar would be capable of producing a 50-digit number of axions. Because of the strong electromagnetic field around the pulsar, a fraction of these axions could convert into observable light. That is: if axions exist at all—but the mechanism can now be used to answer just that question. Just look at pulsars, see if they emit extra light, and if they do, determine whether this extra light could be coming from axions.

Simulating a subtle glow

As always in science, actually performing such an observation is of course not that simple. The light emitted by axions—detectable in the form of radio waves—would only be a small fraction of the total light that these bright cosmic lighthouses send our way. One needs to know very precisely what a pulsar without axions would look like, and what a pulsar with axions would look like, to be able to see the difference—let alone to quantify that difference and turn it into a measurement of an amount of dark matter.

This is exactly what a team of physicists and astronomers have now done. In a collaborative effort between the Netherlands, Portugal and the U.S., the team has constructed a comprehensive theoretical framework which allows for the detailed understanding of how axions are produced, how axions escape the gravitational pull of the neutron star, and how, during their escape, they convert into low energy radio radiation.

The theoretical results were then put on a computer to model the production of axions around pulsars, using state-of-the-art numerical plasma simulations that were originally developed to understand the physics behind how pulsars emit radio waves. Once virtually produced, the propagation of the axions through the electromagnetic fields of the neutron star was simulated. This allowed the researchers to quantitatively understand the subsequent production of radio waves and model how this process would provide an additional radio signal on top of the intrinsic emission generated from the pulsar itself.

Putting axion models to a test

The results from theory and simulation were then put to a first observational test. Using observations from 27 nearby pulsars, the researchers compared the observed radio waves to the models, to see if any measured excess could provide evidence for the existence of axions. Unfortunately, the answer was "no"—or perhaps more optimistically: "not yet." Axions do not immediately jump out to us, but perhaps that was not to be expected. If dark matter were to give up its secrets that easily, it would already have been observed a long time ago.

The hope for a smoking-gun detection of axions, therefore, is now on future observations. Meanwhile, the current non-observation of radio signals from axions is an interesting result in itself. The first comparison between simulations and actual pulsars has placed the strongest limits to date on the interaction that axions can have with light.

Of course, the ultimate goal is to do more than just set limits—it is to either show that axions are out there, or to make sure that it is extremely unlikely that axions are a constituent of dark matter at all. The new results are just a first step in that direction; they are only the beginning of what could become an entirely new and highly cross-disciplinary field that has the potential to dramatically advance the search for axions.

More information: Dion Noordhuis et al, Novel Constraints on Axions Produced in Pulsar Polar-Cap Cascades, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.131.111004

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