Targeting Entire Galaxies in Axion Search

Two independent teams have searched for axions using x-ray observations of entire galaxies, setting some of the strictest constraints to date on the properties of these dark matter candidates.

By **Michael Schirber**

Axions are one of the hottest tickets right now for those looking to go beyond the standard model of particle physics. These hypothetical particles could offer a solution to problems with the theory of the strong force, and they might give evidence for string theory. Axions could also explain the mysterious dark matter. Researchers are searching for axion signals coming from a host of sources that include particle collisions, strong magnetic fields, and nearby stars.

This composite image shows the starburst galaxy M82 in x-ray (blue), optical (orange), and infrared (red) wavelengths.

Credit: X-ray: NASA; CXC; JHU/D. Strickland. Optical: NASA; ESA; STScI; AURA; The Hubble Heritage Team. IR: NASA; JPL-Caltech; Univ. of Ariz./C. Engelbracht

Two separate axion-hunting groups have turned their gaze to a new potential source: starburst galaxies [**1**, **2**]. These giant stellar nurseries could be the biggest axion factories in the Universe. No signal was found in data from the x-ray telescope used by both groups, but the researchers hope to extend their search to other galactic targets.

The axion was originally proposed in the late 1970s as a way to solve the so-called strong-*CP* problem. But over the years, theorists have predicted other types of axions. Certain models of dark matter, for example, assume that an axion-like particle mediates interactions between other dark matter particles. And some models in string theory predict the existence of a multitude of axions, each with a different mass. “Axions are some of the best motivated candidates at the moment for physics beyond the standard model,” says Benjamin Safdi from the University of California, Berkeley.

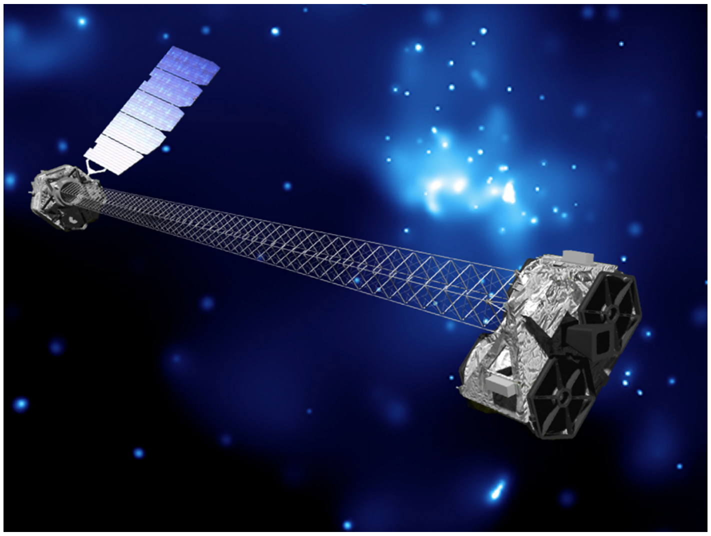
Many experiments have hunted for axions. Researchers have tried to create axion signals in the lab using magnets, as some models assume that an axion will convert into a photon (and vice versa) in a strong magnetic field. Other experiments have scoured particle-collider data for axion hints. However, axions are thought to have feeble interactions with other known particles. “This means that you have to smash a lot of particles against each other so that you have the chance of observing something,” says Edoardo Vitagliano from the University of Padua in Italy.

Generating a multiparticle smashup in a lab is hard to do, so a popular alternative is to study astrophysical sources where particles are constantly colliding at high energy. One of the first axion searches targeted the Sun, but subsequent work has looked at other stars in our cosmic neighborhood (see **Viewpoint: Particle Physics in the Sky**). The idea here is that axions would form in high-energy collisions within the stellar core and then stream out into surrounding space—much like neutrinos do. “We think of stars as axion factories,” Safdi says. “The Sun is the closest and thus the simplest factory to deal with, but there are maybe better sources out there.”

Models suggest that more massive stars should produce axions at a higher rate than smaller-mass stars, like our Sun. The interiors of these stars are hotter, meaning that there are more high-energy thermal photons that can convert into axions through an electromagnetic interaction called the Primakoff process. Previous work looked for axion evidence in the light coming from Betelgeuse, a nearby massive star [**3**]. Safdi and his colleagues performed a similar search in nearby stellar clusters that host massive stars [**4**]. Now he and his graduate student Orion Ning have extended this search strategy to an entire galaxy with billions of stars [**1**]. In a separate study, Vitagliano and his colleagues perform a similar galaxy-wide analysis, but they assume a much heavier axion [**2**].

“We’ve taken this factory analogy to the extreme,” Safdi says. To compute the axion output of an entire galaxy, the researchers needed a model for each type of star in the galaxy, based on its mass and its evolution. Stars that weigh more than 20 times the Sun’s mass should be the brightest in axion emission, as they are able to reach higher internal temperatures by burning helium and other heavy elements. But these stars don’t live very long, so there is a bit of a trade-off between mass and lifetime, Vitagliano explains.

With that trade-off in mind, the best place to find lots of young, massive stars is in a so-called starburst galaxy, where star formation is rampant. The Cigar Galaxy, M82, is one such galaxy. “M82 is very well studied, and among starburst galaxies, it’s close by,” Vitagliano says. Both teams considered M82, while Safdi and Ning also analyzed data for M87, a more distant galaxy located in a galaxy cluster having strong magnetic fields.



Artist’s concept of the NuSTAR telescope. The satellite’s x-ray optics module (right) is separated from the detectors (left) by a 10-m mast that was deployed after launch.

Credit: NASA; JPL-Caltech

The researchers looked for axion signatures in x-ray data from the Nuclear Spectroscopic Telescope Array (NuSTAR). Launched in 2012, this NASA telescope observes the sky in the 3–79 keV energy range and achieves high spatial resolution thanks to a 10-m mast that allows the focusing optics to be separated from the detector. The teams analyzed archival data on M82 and M87, searching for spectral distortions that would arise from axions produced in the galaxies.

Although both teams utilize the same NuSTAR data, they are not looking for the same type of axion. Safdi and Ning assume a lightweight axion (with a mass smaller than 10^{-9} eV/c^2), which could convert into an x-ray photon as it passes through galactic magnetic fields. As it turns out, starburst galaxies have strong magnetic fields, and thus they should be relatively efficient at converting their axion production into a detectable photon signal.

By contrast, Vitagliano and colleagues consider heavy axions (around 10^5 eV/c^2), which are too massive to convert to photons through the same magnetic-field-induced process. Instead, these massive axions are expected to be unstable, spontaneously decaying in a relatively short time into observable photons. In both the light- and heavy-axion cases, the signature is an excess of x-ray photons coming from the direction of the starburst galaxy. “If these particles exist, they would outshine what you already observe in x rays," Vitagliano says. No signal was seen by either team, allowing them to place new constraints on axions in their respective mass ranges.

"It's been known for many years that if axions exist, then the hot cores of stars should essentially work like axion factories," says axion expert Ciaran O'Hare from the University of Sydney. He says that Safdi and Vitagliano and their colleagues have tested this premise by repurposing astronomical observations. "We are gaining new insights into axions by looking for them in data collected by astronomers who are interested in these galaxies for entirely different reasons." But galaxies are complicated astrophysical environments, says Samuel Witte, an astroparticle theorist from the University of Oxford, UK, so a lot of the current effort is devoted to modeling axion production and characterizing the uncertainties associated with astronomical observations and theoretical predictions.

In the future, the teams plan to look at a broader set of axion-production mechanisms, such as electron interactions or nuclear transitions. It may turn out that other galaxies are even better factories. "And hopefully, one of these times, we'll find something, but I have no idea where it will be in this very broad parameter space," Safdi says.

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REFERENCES

1. O. Ning and B. R. Safdi, "Leading axion-photon sensitivity with NuSTAR observations of M82 and M87," **Phys. Rev. Lett. 134, 171003 (2025).**
2. F. R. Candón *et al.*, "NuSTAR bounds on radiatively decaying particles from M82," **Phys. Rev. Lett. 134, 171004 (2025).**
3. M. Xiao *et al.*, "Betelgeuse constraints on coupling between axionlike particles and electrons," **Phys. Rev. D 106, 123019 (2022).**
4. C. Dessert *et al.*, "X-Ray searches for axions from super star clusters," **Phys. Rev. Lett. 125, 261102 (2020).**