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QnAs with Katherine Freese

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The scope of Katherine Freese's research encompasses no less than the history and composition of the universe. Only 5% of the universe is composed of ordinary matter. Freese is interested in the dark side—the 95% composed of dark matter and dark energy. A theoretical cosmologist, she explores how the physics of subatomic particles influences large-scale astronomical objects such as stars and galaxies. She pioneered a theory behind underground dark matter detection experiments (1) and continues to explore the properties of dark matter and dark energy. A professor of physics at the University of Texas at Austin, Freese was elected to the National Academy of Sciences in 2020. Her Inaugural Article (2) introduced four objects imaged by the James Webb Space Telescope (JWST) that may be examples of a theoretical type of star called a dark star—as bright as an entire galaxy, yet relatively cool. PNAS recently spoke to Freese about the significance of candidate dark stars for cosmology.

PNAS: What was your path into cosmology?

Freese: I was born into a scientific family. Both parents were molecular biologists and discussed science around the dining room table. The idea of a woman scientist was not at all foreign to me. I taught myself to read before the age of four; I don't remember not knowing how to read. My favorite thing to do was books and literature. I was not one of these kids who liked looking at the stars. I went to MIT at age 16. But before that, I hadn't had any physics, so I went to Exeter summer school. At first, I was intimidated. But then we talked about special relativity, and it was so amazing that I had to learn more.

I majored in physics and transferred to Princeton after freshman year. Princeton was really hard, and it burned me out. So I took two years off to travel the world and got stuck in Japan with appendicitis. In the hospital, I started reading a book on special relativity by Taylor and Wheeler (3). I thought, "I need more. I need more!" So in August, I contacted Columbia University, where I'd previously been accepted to graduate school and I said, "Hey, can I start next month?" They said yes.

Two years later, as a high-energy experimental student at Columbia, I was living at Fermilab, the particle accelerator outside of Chicago. I wanted to get into the city, so I drove in to take a University of Chicago cosmology class from David Schramm. That course changed my life. I ended up spending more time thinking about cosmology than working in the lab. I connected with Schramm, switched to the University of Chicago, and became his student. That's how I got into cosmology.

[Schramm] was a very inspiring man, one of the founders of particle astrophysics. Unfortunately, he died at 52 flying his own plane in Colorado. He was very influential. His students got faculty jobs all over the place. Advice to students: Find a great mentor and check out what has happened to previous students, because if they've gotten good jobs, then this is somebody who knows how to help you network.

Katherine Freese. Image credit: Marica Rosengard (photographer).

PNAS: You are an athlete as well, with experience in swimming, baseball, and water polo. What have you learned from sports that has carried over into your scientific career?

Freese: I do some kind of sport every day. The high point of my athletics was when I played twice in the National Collegiate Water Polo championships after I became a professor. When I was a little kid, the boys in the neighborhood would come to our corner lot to play basketball and baseball. I think that helped me in physics. I was one of the earliest women in physics, the second female physics major at Princeton. That was hard, but the university as a whole had

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ramped up quickly to one-third female. MIT was a tougher spot for women when I started college and again later as an assistant professor. One of the hardest periods of my life was when I had a newborn baby and was told by the chairman that maternity leave was a benefit MIT could not afford.

I'm really happy to see progress on several fronts. Most universities now have maternity and even paternity leave. The world has gotten a little more sensible in that regard… I think that's a really important step forward.

PNAS: Introduce us to dark matter.

Freese: Dark matter is dark; it doesn't give off light. But dark matter is most of the mass in the universe. Our bodies, the air we breathe, the chair I'm sitting in, stars, planets, everything… is made of atoms, which are made of quarks. But all of that adds up to only 5% of the content of the universe. The other 95% is the dark side. It's 25% dark matter and 70% dark energy. We think dark matter is made of fundamental particles whose identity we haven't yet discovered. And these fundamental particles are flying around everywhere, with billions of them flying through our bodies every second. It is important to understand what 95% of the universe is made of.

PNAS: What are dark stars and why should they exist?

Freese: One well-motivated fundamental particle candidate is the WIMP, the weakly interacting massive particles. These [particles] feel gravity and the weak force and nothing else. WIMPs are their own antimatter. In the early universe, when all particles interacted with one another all the time, WIMPs would annihilate among themselves. But once the universe expanded enough, the annihilation stopped. And if that annihilation proceeded via the weak force, you get the right abundance for dark matter today.

In 2007, a University of California Santa Cruz graduate student, Douglas Spolyar, wanted to work with me on dark matter. We settled on the very first stars that form in the Universe, inside protogalactic objects. Clouds of molecular hydrogen were collapsing inside these objects. In the standard picture, that cloud would collapse…until it's about a thousandth of the sun's mass, which then starts fusion and can grow to at most 500 times the mass of the Sun. And then it's done. It's too hot to have more stuff falling onto it.

But since the hydrogen cloud is located where there's highly concentrated dark matter, the WIMPs annihilate. Their annihilation products interact with the hydrogen and dump energy into the cloud. So you have a very strange new star we call a dark star (4). It has no fusion and is heated by dark matter. Big puffy beast, but it's not hot. It took us a year to realize that it's actually a star—the four equations of stellar structure are satisfied with this different heat source.

These dark stars can keep accreting and growing to a million times the mass of the Sun, a billion times as bright as the Sun. Once they run out of dark matter fuel, they collapse to big black holes that help make the supermassive black holes seen early in the universe.

PNAS: How can JWST image dark star candidates in ways previous observatories could not?

Freese: JWST can look farther back in time thanks to its infrared sensitivity. As the universe expands, the wavelength also expands. So if there's visible light that's emitted at the time of first star formation, that wavelength gets stretched. You need a telescope with infrared sensitivity to look that far back in time.

PNAS: What has JWST found?

Freese: JWST now has 700 high-redshift candidates and good spectra for nine. Five of them are available to the public. And of those five, four of them are in the JWST Advanced Deep Extragalactic Survey, or JADES. And of those four, three of them are compatible with being dark stars. So far JWST can't tell the difference between a dark star and an early galaxy of ordinary stars.

In the future JWST will find magnified objects, which look brighter because of lensing by the intervening material between the distant object and JWST. With these, we'll be able to tell the difference between dark stars and early galaxies via two signatures: a detailed spectrum and whether it's a tiny point object or an extended one. If there's only hydrogen and helium spectral lines, that would be a dark star. If you see anything else, those other elements would be made by later stars. A dark star is going to look small, whereas a galaxy's going to look big in size.

JWST is just getting started. It already has highly magnified objects and will find many more. So we will get clean spectra on tons and tons of objects from the early universe. The upcoming Nancy Grace Roman Space Telescope will also be able to see dark stars. It doesn't go as far back in time but has a larger field of view. So it'll be able to find the candidates more quickly.

PNAS: How would confirming dark star candidates change astronomy?

Freese: It would be an entirely new type of star. It took a long time to realize that nuclear physics provides the power source for the Sun via fusion in its core. And if particle physics is again affecting stars here, that's an important contribution. Also, in principle, you could use dark stars to identify the nature of the dark matter that has now been a mystery for 90 years.

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2. C. Ilie, J. Paulin, K. Freese, Supermassive Dark Star candidates seen by JWST. *Proc. Natl. Acad. Sci. U.S.A.* **120**, e2305762120 (2023).
3. E. F. Taylor, J. A. Wheeler, *Spacetime Physics* (W.H. Freeman and Company, 1966).
4. D. Spolyar, K. Freese, P. Gondolo, Dark matter and the first stars: A new phase of stellar evolution. *Phys. Rev. Lett.* **100**, 051101 (2008).