Shedding LIGHT on DARK STARS

Bizarre stars powered by dark matter may have been the first to form after the Big Bang.

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All Illustrations by *S&T:* Casey Reed

The scientific version of Genesis tells us that the universe sprang into being 13.7 billion years ago and that the first denizens of that new realm — stars — blazed into existence about 100 million years after the Big Bang. Even by stellar standards, the first stars were titans. They were bigger, brighter, and burned faster than any stars in existence today (*S&T:* May 2006, page 30).

But if a new theory of star formation is correct, the stellar first born were even stranger beasts than scientists previously thought because of how they interacted with dark matter, the unseen "substance" that scientists think makes up more than 80% of the universe's mass.

Stars like our Sun rely on the fusion of light elements into heavier ones to counteract their own immense gravities and to keep them from imploding. But some of the most popular theories in physics suggest dark matter consists of particles that can act as their own antiparticles (*S&T:* April 2009, page 22). This raises the intriguing possibility that the first stars were powered by the self-annihilation of concentrated dark matter in their cores. Such "dark stars" would have been cooler but more colossal than their fusion-driven brethren. "They're still stars, made primarily of hydrogen and helium. Less than 1% of their mass is dark matter," says Katherine Freese (University of Michigan).

Freese, along with Paolo Gondolo (University of Utah) and Doug Spolyar (University of California, Santa Cruz), were the first to investigate dark stars in 2006. The team says that if dark stars existed, they could have altered the chemistry of the early universe by delaying the birth of "normal" first-generation stars — called Population III stars — by up to a billion years. Dark stars could also explain why supermassive black holes appear to have formed so soon after the Big Bang.

Dark-Star Evolution

In the aftermath of the Big Bang, the universe was a sea of smoothly distributed particles, featureless and dark. A smattering of the particles consisted of familiar, or *baryonic*, matter, but the vast bulk of it was dark matter. Over time, the dark-matter particles coalesced into a complex spider-web-like structure made up of filaments that intersected to form nodes, or *halos*. Baryonic matter flowed along the filaments, drawn by gravity into the massive halos, where it assembled into gas clouds. The clouds collapsed gravitationally into luminous knots of gas, creating the first protostars. As the protostars grew in mass, they contracted in size until their cores reached a critical density and temperature that ignited nuclear fusion.

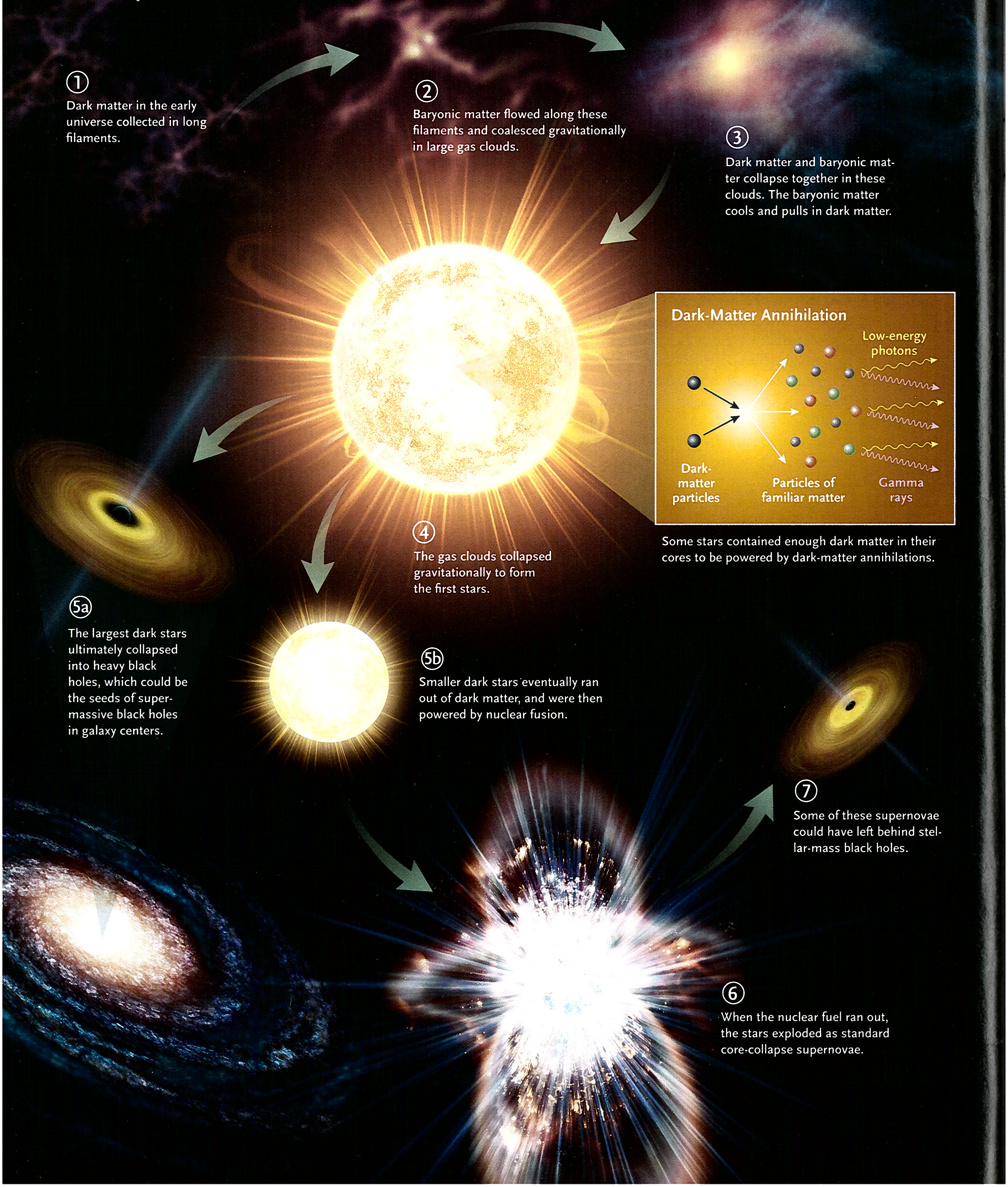
In this standard scenario, dark-matter halos are stellar wombs where baryonic matter collected and matured into stars, but dark matter does not affect star formation directly. However, computer models by Freese and her colleagues challenge this idea. "In the standard picture, a protostellar cloud collapses until it's small, dense, and hot enough to get fusion going," says Freese. "We're saying there's an intermediate stage where it sits for a very long time with this dark-matter power instead."

In this revised stellar history, dark matter was not just the backdrop against which the lives of the first stars played out. Dark matter's spatial density in the early universe was much higher than it is today because the universe — still in the early stages of expansion — was a much smaller place. The first stars were immersed in dark matter. Like a phantom wind, dark-matter particles blew through and around the first stars. The first protostars attracted dark-matter particles and concentrated them in their cores. If the protostar's dark-matter density exceeded a certain threshold, the particles collided and self-annihilated in an energetic spray of photons, neutrinos, and electrons. During dark-matter self-annihilation, mass converts into energy much more efficiently than in nuclear reactions, so a small amount of dark matter can power an entire star.

Importantly, the dark-matter-burning phase prevents further gravitational contraction of the protostar, essentially "freezing" it in an embryonic stage before its nuclear engine can ignite. As a result, dark stars would have been vastly larger and "fluffier" than normal Population III stars. They would have had diameters ranging from about 1 astronomical unit (the average distance between the Sun and Earth) to perhaps 30 a.u. — about Neptune's distance from the Sun. And whereas a normal Population III star might contain 100 solar masses (*S&T*: May 2006, page 30), recent studies suggest the largest dark stars might have had masses between 1,000 and 10,000 Suns. Dark stars would have been yellow-orange like our Sun, but the largest ones might have shined a billion times brighter due to their huge surface areas.

STARS COMPARED The characteristics of stars are determined by their compositions, masses, and energy sources. Huge stars such as dark stars and red supergiants have powerful energy sources, which puff up their atmospheres, making their visible surfaces relatively cool. The name "dark star" is actually a misnomer. Due to their huge surface areas, they would have shined with the intensity of millions of Suns. Like dark stars, Population III stars existed only in the early universe, but they were powered by nuclear fusion rather than by dark-matter annihilation.

Life Cycle of Dark Stars



"Standard Population III stars were hotter and bluer by comparison," says Freese.

Computer simulations predict that dark stars can survive so long as the surrounding dark-matter density remains high. At a minimum, dark stars should have survived for about a million years, and perhaps even billions of years if the dark-matter halo is very large or if there is an influx of dark-matter particles from outside sources. It's possible that some primordial dark stars might have survived to the present day. "We might find these first stars still shining. That would be tremendous," says Igor Moskalenko (Stanford University).

Cosmic Consequences

The fate of dark stars once they run out of dark-matter fuel depends upon their mass. Dark stars with only a few hundred solar masses could become "unfrozen" after exhausting their dark-matter reserves. They would revert to normal fusion-driven stars and live for another million years or so before exploding as supernovae and seeding the universe with their heavy elements.

But a return to normal stellar life would be out of the question for the most-massive dark stars. Their incredible mass would cause them to collapse directly into black holes. Dark stars could thus explain how quasars — bright galaxies with supermassive black holes at their centers — existed only a few hundred million years after the Big Bang, sooner than most current theories predict. "There's just not enough time in the current theories without dark stars for black holes with only a few solar masses to come together and form the million-solar-mass black holes that are required to explain quasars," says Gondolo.

Dark stars may also have played a role in ending the cosmic *dark ages,* a period of total darkness after the Big Bang when newly formed hydrogen and helium atoms absorbed all of the universe's light. According to standard theory, the ultraviolet light of several generations of stars and galaxies was required to break apart, or ionize, the atoms and make the universe transparent again. But dark stars should have given rise to larger and more energetic fusion-driven stars, and this could have sped up the reionization of the universe. Freese says dark stars could also have delayed reionization by delaying the formation of standard Population III stars. "I'm hedging on that one," she says. "Dark stars are going to affect reionization, but we don't know in what direction yet."

Lars Hernquist (Harvard-Smithsonian Center for Astrophysics) says dark stars would definitely have changed things. "The early universe would have looked quite different because these stars would have been a much longer-lived source of radiation than if they were to die after only a million years or so," he says.

Hernquist adds, however, that while dark stars are interesting, they are still fairly speculative, "because the modeling used by the scientists makes several assumptions and their calculations are fairly simple."

For example, says Avi Loeb (Harvard-Smithsonian Center for Astrophysics), it's possible that the dense central regions of dark-matter halos — called cusps — were fragile and easily disrupted by interactions with baryonic matter. "Until the existence of such cusps is demonstrated to be a robust result based on three-dimensional numerical simulations, I would not be convinced that dark stars could exist in reality," Loeb says.

Finding Dark Stars

The first evidence for dark stars might come not from computer models, but from astronomers. Fabio Iocco (Paris Institute of Astrophysics, France) reasons that dark stars should postpone the supernovae of standard Population III stars by tens to hundreds of millions of years. "The best signature we might have is a delay in Population III supernovae by a certain time due to the dark-star mechanism," Iocco says. Scientists speculate that if the delay is sufficiently long, the first supernovae could be observed by future space telescopes.

Next-generation satellites might also be powerful enough to detect ancient light emitted by primordial dark stars that disappeared long ago. Theories predict that the light from early dark stars should be shifted to far-infrared wavelengths by the time they reach us. "We were hoping for an infrared detection with the James Webb Space Telescope, but our dark stars turn out to be just slightly too dim for it," says Gondolo. "We're exploring other ways."

Alternatively, space missions might detect frozen dark stars that have managed to survive to the present epoch. Mass and chemical compositions being equal, dark stars should be bigger and colder than fusion-driven stars. They should also be similar in temperature to our Sun, but about a million times brighter. If astronomers ever find a star with these peculiar properties, it could be evidence that some astral relics from the dawn of time are still with us. ✦

WHAT IS DARK MATTER?

Scientists have yet to identify the nature of dark-matter particles, but many physicists think they are weakly interacting massive particles, or WIMPs. These wispy particles are predicted by supersymmetry, a theory that postulates that all the known particles have heavy partners, most of which have decayed since the Big Bang. Because the surviving WIMPs interact with familiar matter only through the weak nuclear force and gravity, nature's two weakest forces, these particles are exceedingly difficult to detect.

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