From Here to Eternity

Tracking the future of the cosmos

By RON COWEN

Psst. Want to know the fate of the universe?

Fred C. Adams and Gregory P. Laughlin say they've foretold the future. Instead of relying on crystal balls and Tarot cards, these cosmic fortune-tellers use the laws of physics to trace the long-term evolution—and ultimate demise—of stars, galaxies, and black holes.

Emphasis is definitely on the long term. Adams and Laughlin's study, described in this month's REVIEWS OF MODERN PHYSICS, encompasses birth and death in the cosmos, beginning 1 million years after the Big Bang and ending a nearly unfathomable 10^{100} years later. In comparison, the universe today is a measly 10^{10} years old.

From a star-filled cosmos to a vast sea of subatomic particles, the University of Michigan astrophysicists find that almost nothing lasts forever—except the universe itself.

Adams embarked on his tour of the future in January 1996, when he seized the chance to teach a course in a special program on death, extinction, and the future of humanity. The course, he realized, would provide a wonderful excuse for studying in detail the death of stars and the demise of galaxies, but he hadn't figured it would lead to a 50-page opus.

Shortly before Adams began teaching the course, he met Laughlin, a new postdoctoral fellow in the physics department in Ann Arbor. "He showed up in Michigan, and we just started talking about everything," recalls Adams. "As we sat and talked, we thought of more and more things to do. . . . It was just a landslide [of ideas]."

In contemplating the fate of the universe, Adams and Laughlin followed in the footsteps of several other cosmologists, notably Freeman J. Dyson of the Institute for Advanced Study in Princeton, N.J. In his 1979 article "Time Without End," Dyson traced the history of the universe, assuming that the cosmos will expand forever because its density of matter is too low for gravity to slow it down. Recent observations seem to favor such an open universe, which Adams and Laughlin adopt in their study.

In another respect, however, the researchers part company with Dyson. They assume the still-controversial notion that protons will ultimately decay.

"Dyson wrote a very excellent article, but in the 20 years that have elapsed since that time, a lot of new physics [has come to light]," says Adams. Dyson hoped to make studies of the future a mainstream part of science, Adams adds, and encouraged other workers to carry on.

"We carried it as far as we can go."

The scientists say that death in the universe unfolds in four acts. In the present, earliest era, the energy generated by stars drives astrophysical processes. Though the cosmos is already 10 to 20 billion years old, the vast majority of stars have barely begun to twinkle.

Stars shine by fusing hydrogen nuclei at their core, forging helium and heavier elements. Massive stars burn brightest but die fastest. Stars as heavy as the sun, for example, live for about 10 billion years. Yet galaxies, whose fate is determined by the stars within them, don't plunge into darkness until much later.

That's because 80 percent of the stars in the universe have less than 80 percent of the mass of the sun and live far longer, Laughlin explains. "During the amount of time we've had so far, [low-mass stars] have not even begun to evolve," he says.

These lightweight stars burn their hydrogen at a miserly rate but ultimately consume a higher proportion of it than more massive stars do. Constant churning of their gaseous layers mixes 99 percent of the hydrogen in low-mass stars into their hot cores, where nuclear fusion reactions burn it. In contrast, stars as massive as the sun mix their gases less thoroughly and use up only 10 percent of their hydrogen before dying.

In about 10 trillion years, the emissions of the lowest-mass stars—those with only 8 percent of the sun's mass—will revive fading galaxies, temporarily boosting their brightness to what it is today. Adams and Laughlin calculate that even these last surviving stars will die after 100 trillion years. At about that time, the researchers note, galaxies will have run out of gas—the raw material for making new stars. With star formation halted, the period that Adams and Laughlin call the stelliferous, or star-filled, era draws to a close.

The second act contains a much smaller and more quiescent cast of characters. As the universe continues its inexorable expansion, energy reserves dwindle and galaxies shrink, with more and more material clustering at their centers.

Brown dwarfs, objects that don't have quite enough mass to shine as stars do, linger on. Gravity will have already drawn together the burned-out remains of dead stars, and these cinders will have formed the densest objects in the cosmos—white dwarfs, neutron stars, and black holes.

After a star ranging from 0.08 to 8 times the mass of the sun has run out of fuel, its core collapses to become a white dwarf, an object as small as Earth but 1 million times denser. Heavier stars, up to about 30 times the sun's mass, typically end their lives as neutron stars, which have densities so high that protons and electrons are squeezed together in a giant sphere composed entirely of neutrons. Even more massive stars become black holes, objects in which gravity reigns supreme, preventing even light from escaping.

Adams and Laughlin call this epoch the degenerate era, because white dwarfs and neutron stars exist in what physicists call a degenerate state. Despite the tug of gravity, the particles within these objects—electrons and neutrons, respectively—can't squeeze together beyond a certain density. Quantum mechanics forbids identical subatomic particles with similar velocities from occupying the same region of space. This creates an internal quantum mechanical pressure that keeps the electrons and neutrons from contracting any further.

Over an enormous span of time, from 10^{14} to 10^{30} years, white dwarfs will capture and devour a considerable amount of dark matter, the invisible material thought to reside in the haloes of galaxies. Astronomers believe that dark matter accounts for the high rotation rate of the outer parts of galaxies, keeps clusters of galaxies from flying apart, and fosters the emergence of structure in the infant universe.

The type of dark matter that Adams and Laughlin assume exists is known as weakly interacting massive particles (WIMPS). In addition to being sucked into white dwarfs, WIMPS can collide with and annihilate each other. So by 10^{30} years, the cosmos will have dissipated the dark matter surrounding galaxies, according to the researchers.

Amid the decay are a few bright

moments. A handful of new stars will form, Laughlin notes, when the chance collision of two brown dwarfs creates a single object massive enough to sustain hydrogen burning. Mergers between white dwarfs may lead to an occasional supernova explosion, and colliding neutron stars generate even more powerful fireworks.

"Such events are impressive today," says Laughlin. "They will be truly spectacular within the cold and impoverished environments of [aging] galaxies."

As time marches on, however, even the white dwarfs and neutron stars disintegrate, undone by the decay of protons, according to Adams and Laughlin. "Proton decay is perhaps the most important process in the future history of the universe," Adams says.

Often thought of as absolutely immutable, the proton might merely be extraordinarily long-lived, according to grand unified theories, which seek a common foundation for seemingly different forces of nature. These theories permit, and some even require, that the number of baryons, elementary particles that include protons and neutrons, is not a strictly conserved quantity. Baryon nonconservation "leads to a whole host of decay channels for the proton," Adams says.

Lawrence M. Krauss of Case Western Reserve University in Cleveland adds that proton decay could be a natural consequence of processes that occurred in the early universe. During the first few seconds after the Big Bang, the universe presumably had nearly equal amounts of protons and antiprotons. Today's cosmos has a far greater number of protons. To reconcile the counts, physicists hypothesize that some protons were created spontaneously. If so, then theory would also allow protons to be destroyed.

Adams and Laughlin assume that the proton will decay in about 10^{37} years—a time scale consistent with limits set by experiments. Given this decay rate, white dwarfs and neutrons stars will evaporate by 10^{40} years, bringing down the curtain on the degenerate era.

The curtain next rises on an empty stage. Welcome to the black hole era, in which gravity has turned entire galaxies into invisible, supermassive black holes.

Black holes are likely to outlive white dwarfs, brown dwarfs, and neutron stars and will continue to increase their girth as they feed on material falling toward the center of galaxies, according to the researchers. Yet even these bizarre beasts will not last forever. Although astronomers and science journalists often describe black holes as objects that never allow light to escape—an accurate enough description for the short term—quantum mechanics suggests that black holes are ultimately leaky. They slowly radiate their energy away.

Through this process, known as Hawking radiation in honor of its discoverer, physicist Stephen Hawking of the University of Cambridge in England, black holes eventually dissipate their enormous mass. A black hole with the mass of a large galaxy will evaporate completely in 10^{98} to 10^{100} years, Adams and Laughlin estimate.

What's left after black holes have vanished? The cosmos, says Adams, may then consist of a diffuse sea of electrons, positrons, neutrinos, and radiation. This last epoch, which the researchers dub the dark era, remains the murkiest. "As time goes on, things become more and more uncertain," notes Adams. "We understand the stelliferous and degenerate eras much more readily."

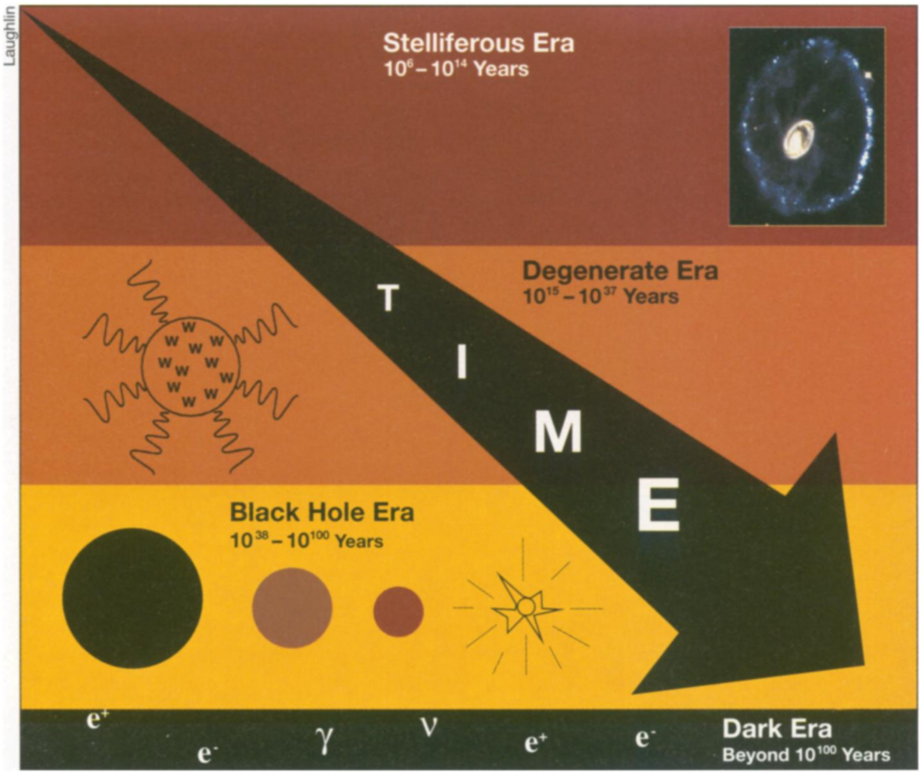
Adams and Laughlin shy away from contemplating the possibility of life in the far future, eons after organisms dependent on water and organic compounds have vanished. They speculate, however, that some sort of network of structures, spread out over unimaginably large distances, might exist and store information.

"There is the possibility for [organized] structure made out of whatever materials are available," says Laughlin. "Obviously, those structures will have extraordinarily low energy and will unfold extraordinarily slowly, but in some sense, if you have lots and lots of time, I think that structure may always continue to exist in the universe."

Another mind-bending possibility is that the nature of physical laws, which Adams and Laughlin assumed for the sake of their calculations would hold constant, may in fact change. In this respect, the universe in the far future may have a surprising link to the cosmos of the distant past.

In the first fraction of a second of cosmic history, as the infant universe began to cool, it may have undergone abrupt phase transitions—changes in structure like the one that occurs when liquid water freezes into ice (SN: 12/7/96, p. 364). Such phase transitions may also occur in the vacuum in the distant future, Laughlin speculates. "When this happens, you can either get new physical laws or you can get a new kind of universe," says Laughlin. "As physical laws change, or as our understanding of physical laws changes, our vision of the future will undoubtedly have to be revised."

In any event, scientists will have a long, long time to think about it. ☐



Laughlin

Tracing the fate of the universe, now about 10^{10} years old. During the current epoch, the stelliferous era, stars dominate the universe. Because they burn more slowly, the lowest-mass stars, red dwarfs, will survive long after sunlike stars have died and become compact objects known as white dwarfs. During the degenerate era, white dwarfs capture a hypothetical type of invisible matter, called WIMPS (w), causing the dwarfs to radiate. In addition, protons decay, destroying the white dwarfs. In the black hole era, black holes (dark circles) slowly radiate away their mass and disappear. Finally, in the dark era, the universe consists of a vast sea of photons (γ), neutrinos (ν), electrons (e^-), and positrons (e^+).