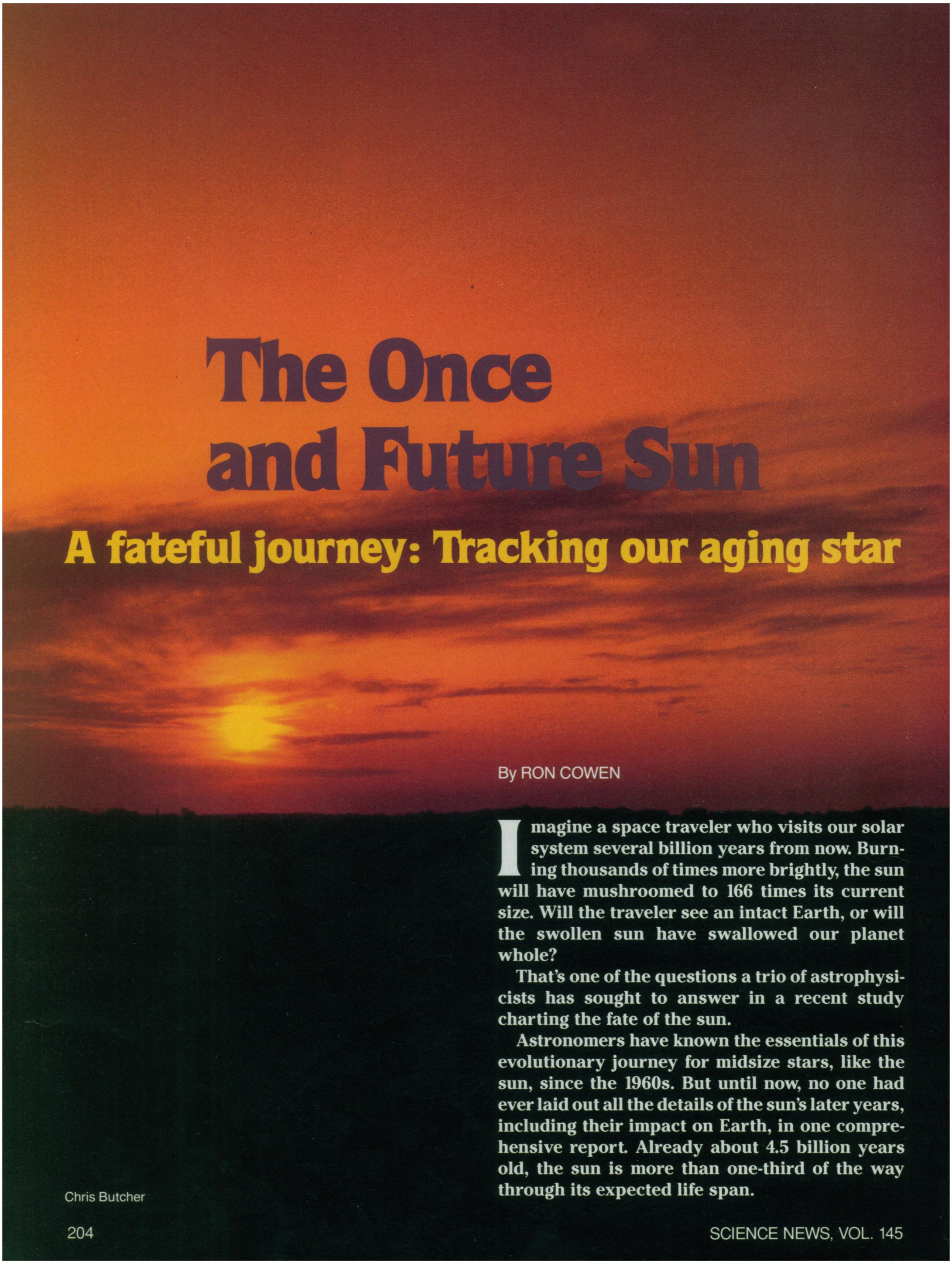


Chris Butcher

The Once and Future Sun

A fateful journey: Tracking our aging star

By RON COWEN

Imagine a space traveler who visits our solar system several billion years from now. Burning thousands of times more brightly, the sun will have mushroomed to 166 times its current size. Will the traveler see an intact Earth, or will the swollen sun have swallowed our planet whole?

That's one of the questions a trio of astrophysicists has sought to answer in a recent study charting the fate of the sun.

Astronomers have known the essentials of this evolutionary journey for midsize stars, like the sun, since the 1960s. But until now, no one had ever laid out all the details of the sun's later years, including their impact on Earth, in one comprehensive report. Already about 4.5 billion years old, the sun is more than one-third of the way through its expected life span.

For I.-Juliana Sackmann of the California Institute of Technology in Pasadena and her colleagues, this study has special significance. It marks the third and last in a series of articles on the life of the sun that the team began writing in the late 1980s (SN: 11/2/91, p.287). Having previously pondered the middle-aged star's past and present, it seemed only natural to explore its future, says Sackmann.

"Tremendous efforts have been made to understand the sun's interior structure and history, but relatively little work has focused on the future of our sun and its final fate," the astrophysicists write in the Nov. 20 ASTROPHYSICAL JOURNAL.

"Studying the evolution of the sun is not how I earn my bread and butter," admits Sackmann, who says she prefers studying more massive stars, which evolve faster and have more dramatic, violent story lines. "But even an ordinary star like the sun is interesting because Earth is here, affected by it."

Throughout its life, a star must battle the very force responsible for its creation: gravity. Gravitational attraction draws together the raw materials that make up a star – gas and dust. But gravity pulls inward relentlessly, shrinking the star to a smaller size. Nuclear fusion, the joining of lighter nuclei to form heavier ones, provides a counterforce. Fusion unleashes vast amounts of energy, which streams outward from the star's interior, opposing gravity. This tug-of-war forces stars to undergo a series of contortions before dying.

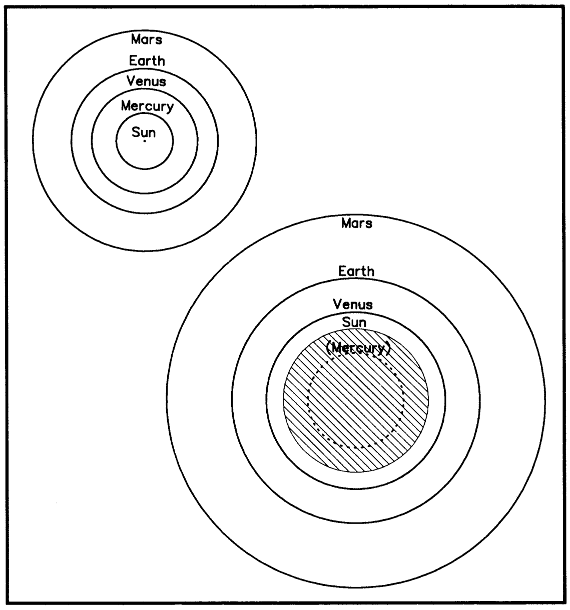
Ballooning and shrinking, brightening and fading, heating and cooling: It's these staccato episodes that Sackmann, Arnold I. Boothroyd of the Canadian Institute for Theoretical Astrophysics at the University of Toronto, and Kathleen E. Kraemer of Boston University now describe in detail for the maturing sun.

For most of its life, a star remains relatively quiescent, fusing hydrogen to make helium within its core. During this long period of evolution, known as the main sequence, it slowly but steadily brightens.

In its infancy, the sun shone with only 70 percent of its current luminosity, Sackmann and her colleagues note. During the next 1.1 billion years or so, its luminosity will increase 10 percent. That increase, according to a model proposed in 1988 by James F. Kasting of Pennsylvania State University in University Park, is likely to instigate a runaway greenhouse effect on Earth. The planet's oceans will boil away, destroying life as we know it.

Some 6.5 billion years from now, the sun will have more than doubled its present luminosity and exhausted the supply of hydrogen nuclei at its core. Hydrogen fusion will then move outward to a shell of gas surrounding the core.

As the energy released by the shell of burning hydrogen makes its way through the sun, it will cause the star's outer layers to swell. That will lead to a new phase in the life of the sun. Paradoxically, even as the core grows hotter and denser, the sun's outer envelope expands and cools, growing redder in color. The reddish, bloated envelope of gas surrounding a hot, dense core will mark the sun's transformation into a star known as a red giant.



Credit: Boothroyd

***Top:** Diagram shows current positions of the sun and the four inner planets. **Bottom:** In about 8 billion years, the sun will have engulfed Mercury. Because the sun may lose as much as half its mass as it expands, the other planets may move far enough away to escape destruction.*

After completing this transformation, which takes about 1.3 billion years, the sun will have expanded enormously. Its girth will be 166 times its present size, and its luminosity will be 2,300 times as great, Sackmann's team calculates. At this point, nearly 8 billion years in the future, the voluminous star will begin to encroach on the inner planets. Its radius will fill three-fourths of the 93 million miles of empty space that now exists between the sun and Earth, the astrophysicists write. That's close enough for the star to swallow Mercury and extend beyond the present orbit of Venus.

But as the bloated star expands, it also sheds mass, loosening its gravitational grip. If Venus spirals out as far as Earth's current orbit, it will elude destruction, according to the team. (This assumes that a wind created during this phase of evolution will carry off about a quarter of the sun's mass.)

As gravity continues to shrink the sun's core, now composed almost entirely of helium, it causes the density of this central region to increase and the temperature to rise to about 100 million kelvins. Finally, the extreme heat and density ignite the helium nuclei, which fuse to form oxygen and carbon. When the helium starts burning, the luminosity of the core may reach 10 million times that of the surface. Surprisingly, the visible surface of the sun will become less bright, and its radius will shrink.

"Stars always do the opposite of what you think they'll do," notes Sackmann ruefully. "There's all this violence going on inside, but none of it shows on the outside."

The dichotomy occurs, she and her colleagues explain, because the expanding core of helium cools the surrounding shell of hydrogen gas. As this shell transmits less heat to the sun's surface, the sun's luminosity – and its volume – decrease.

Once the helium has ignited, the sun will enter another quiescent stage. It's as if it had returned to the steady evolution typical of the main sequence, except that it now burns helium at its core instead of hydrogen. But this state of affairs lasts only about 100 million years. Smaller, hotter, and denser than ever before, the solar core behaves like a character in a movie run at high speed, burning its dwindling supply of helium fuel faster and faster.

After the sun has consumed all the helium at its center, the helium in a shell of gas just outside the core ignites. Meanwhile, the outlying shell of burning hydrogen remains intact. At about 12.3 billion years of age, the sun has become a star with two burning shells.

Its nuclear fuel depleted, the sun's core contracts, drawing in the two gas shells around it. This causes the helium shell to undergo a series of explosions, triggering the final phase of expansion and brightening, which will last about 20 million years.

Shedding an additional quarter of its original mass, the expanding sun will extend as far as Earth's present orbit. But by then the planet will have fled, moving out to a path 1.7 times as distant, according to the study. If the sun sheds its mass over a 30 percent longer period of time – a scenario deemed unlikely by the researchers – it might swallow Earth.

After a few million years more, the sun will finally sing its swan song. Ejecting its puffy outer layers, the elderly star will lay bare its smoldering, collapsed core, thus becoming a relic known as a white dwarf (SN: 1/16/93, p.40). Barring a fatal collision with another body in the solar system, Earth will probably remain intact to the bitter end, Sackmann's team speculates.

Our planet, albeit devoid of life as we know it, may orbit the sun forever. □