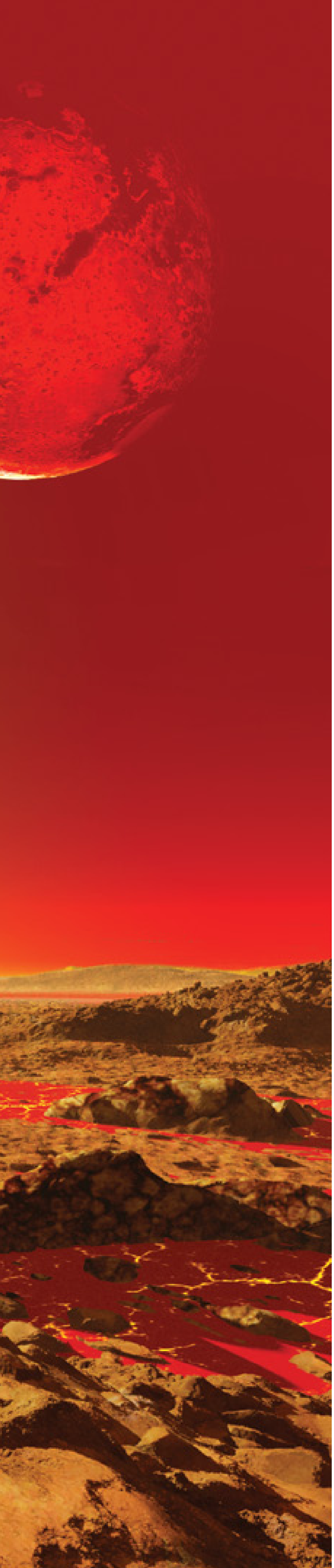
HIGHEST-ENERGY SUPERNOVAE might look quite spectacular from a planet orbiting the exploding star, but any civilization would most likely be obliterated.



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ASTROPHYSICS

SUPER SUPERNOVAE

The largest stars die in explosions more powerful than anyone thought possible—some triggered in part by the production of antimatter

By Avishay Gal-Yam

IN THE MIDDLE OF 2005 THE W. M. KECK OBSERVATORY ON MAUNA KEA IN Hawaii completed an upgrade of one of its giant twin telescopes. By automatically correcting for atmospheric turbulence, the instrument could now produce images as sharp as those from the Hubble Space Telescope. Shrinivas Kulkarni of the California Institute of Technology urged young Caltech researchers—myself among them—to apply for observing time. Once the rest of the astronomy community realized how terrific the telescopes were, he warned us, securing a slot would become very competitive.

Taking this advice, I teamed up with my then fellow postdocs Derek Fox and Doug Leonard to attempt a type of study that previously had been carried out almost solely with the Hubble: hunting for supernova progenitors. In other words, we wanted to know what stars look like when they are about to explode.

For decades theorists have been able to predict which celestial bodies are going to go supernova—for instance, they know that bright blue stars are due to explode soon. But "soon" to an astronomer means within the next million years or so. So, although observing the entire process unfold would enable us to understand it better, just patiently watching an individual star was not an option.

We thought that Keck could help us, and we were granted a single night of observing time in November 2005. As I flew in to the Big Island, I was anxious, hoping for good weather, as we had only one chance to try this new approach. Fortunately, the weather gods cooperated. That evening of observing set me on a research path that ultimately helped to overturn long-standing views of how large stars can become and how these giants die.

At the time, experts maintained that very large stars do not explode; rather they gradu-

Illustration by Ron Miller

ally shrink by shedding mass as stellar wind. Indeed, most theoretical astrophysicists would have said that because of these powerful winds, stars in the present-day universe cannot grow to a massive size in the first place—that they cannot become much heavier than, say, 100 times the mass of our sun.

As a result of our Hawaiian adventure, though, we gradually came to realize that stars of at least 200 solar masses do exist in our current universe and that they end their lives with the most energetic explosions in the universe. Equally surprising, we were also to discover that some of those stars explode in a way quite unlike anything astronomers had ever seen—in a process involving the generation of antimatter at the star's center.

Such enormous stars, and probably even larger ones, were the first celestial bodies to form from primordial gas in the universe's early history. Their way of exploding thus tells us how the elements they produced could spread around the cosmos and ultimately sow the seeds of today's suns, planets and people.

AN UNLIKELY START

IN OUR ONE TIME at the telescope, Fox, Leonard and I hoped to observe an active supernova and then, by looking at archival images shot by the Hubble, find an image of the star before it exploded. We therefore needed to look for a supernova in one of the many galaxies the Hubble had imaged in the past. The difficult part of finding our target in a Hubble photograph would be figuring out which star, among the billions in a galaxy, was the one that blew up. To do so, we would need to measure the location of the supernova with great precision. Before the advent of adaptive-optics systems such as Keck's, that was possible only through the Hubble itself. Even then, the task was so challenging that astronomers had managed to positively identify only three progenitors.

Among the supernovae active at the time, we selected one named SN 2005gl. Other groups would have considered it a poor choice, and for good reason: researchers who seek supernovae progenitors typically look within a radius of about 60 million light-years of Earth; this one was more than three times farther than that—about 200 million light-years away. For us to find the progenitor of SN 2005gl in Hubble images, that star would have to have been among the most luminous ever observed. The likelihood of success was low, but we felt that sometimes only by aiming at long shots can you reap huge rewards.

Our gamble paid off. After measuring SN 2005gl's position with Keck data, we looked at a Hubble image and saw something there that looked like a star, although we could not be sure. If it was a single star, its brightness (perhaps a million times that of the sun) suggested it was massive—100 times the sun's mass. Yet given prevailing opinion that such a heavyweight should not explode at all, most astronomers would have thought it more plausible that the dot of light in the Hubble image came from a cluster of smaller, fainter stars that together produced the brightness we saw. And our data could not rule out this possibility—yet.

ANOTHER STRANGE BLOWUP

EVEN THOUGH our result was inconclusive, I became increasingly interested in finding observational evidence speaking to the fate of the most massive stars. But science rarely follows a straight line from asking a question to finding an answer. I was thinking of stellar explosions of an entirely different kind—those called gamma-ray bursts—when a chance event in 2006 led to another surprising finding, which suggested not only that giant stars might go supernova but also that they could do so in a startling way.

This new chapter in the story began with another night at the Keck observatory in 2006. This time, however, the gods seemed much less kind: the weather was terrible. I sat by the control computer and waited, as hours went by. Just as I was beginning to wonder whether my long trip back had been in vain, the clouds thinned out. The sky did not exactly clear up, but you could see some stars. I decided to observe the brightest supernova explosion visible at that time, an unusually luminous event called SN 2006gy, which then University of Texas at Austin graduate student Robert Quimby had discovered eight days earlier using a telescope less than one-twentieth the size of the giant Keck reflectors. I managed to observe for 15 minutes until the clouds thickened again, this time for good. It seemed like the night was a total loss.

But later, a team led by my Caltech colleague Eran Ofek analyzed the data I had obtained, and SN 2006gy turned out to be the most luminous supernova explosion ever found to date. A parallel study led by Nathan Smith, then at the University of California, Berkeley, came to a similar conclusion. It made no sense. None of the types of supernovae we were aware of could generate so much light. SN 2006gy was in a galaxy that had not been imaged by Hubble before, so we also had no way of studying its progenitor star in detail. Judging from the violence of its explosion, though, the star probably weighed at least 100 solar masses.

We thought of several possible explanations for the luminosity, two of which seemed the least implausible. The first was that the extremely bright light was heat radiation from a shock wave that formed as the supernova's explosive debris caught up with the slower stellar wind that the star itself had emitted before exploding and swept that stellar wind away. The second option we considered was radioactivity. Supernovae synthesize new elements, largely in the form of radioactive isotopes that later decay into other, more stable ones. Perhaps this giant explosion synthesized a huge amount of radioactive material, whose slow decay injected energy into an expanding cloud of stellar debris and made the cloud glow in fluorescent light. But what could produce enough radioactive material to explain such outrageous luminosity?

That last question grabbed our interest. To try to answer it, we began to review past theoretical work. We stumbled on old, dusty theoretical papers from the late 1960s by three young astrophysicists—Gideon Rakavy, Giora Shaviv and Zalman Barkat. They had proposed a new way that a star could blow up.

Stars shine because their cores are dense and hot enough

IN BRIEF

In recent years several supernovae have turned out to be more powerful and long-lasting than any observed before. **Archival images** showed that the stars that gave rise to some supernovae were about 100 times as massive as the sun: according to accepted theory, stars this big were not supposed to explode.

Some supernovae may have been thermonuclear explosions triggered by the creation of pairs of particles of matter and antimatter.

The first generation of stars in the universe, which created the materials that later formed planets, may have exploded through a similar mechanism.

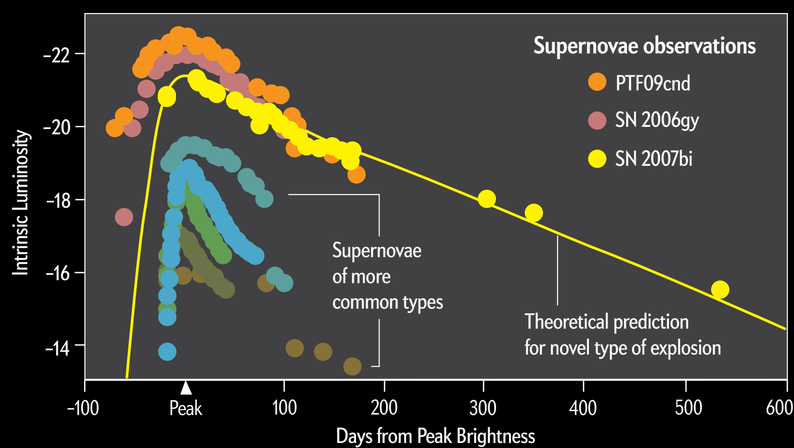
that hydrogen atoms fuse, turning into helium and heavier elements and releasing energy. Those two parameters—density and temperature—by and large control the physics of the core of a massive star and the star's evolution. In general, as time progresses, the core gets denser and hotter. The core then crosses successive thresholds toward the fusion of increasingly heavy elements—first helium to carbon, then carbon to oxygen, and so on. Each stage between thresholds may last thousands to billions of years, depending on how fast the star's nuclear burning affects its core temperature and pressure.

Rakavy and company calculated what would happen when a very massive star, perhaps hundreds of times more massive than the sun, reaches the stage at which its core is mostly oxygen. In lesser stars, we know what is next: the star contracts, and its core heats up until conditions allow the nuclear fusion of oxygen into silicon. But in a hypergiant, the theory said, the core would contract under gravity and heat up without becoming very dense. So instead of oxygen fusion, something else would happen: physicists call it pair production.

SUPERNOVA OBSERVATIONS

The Brightest of the Bright

Supernova explosions studied by the author and his collaborators in the past few years have turned out to be the most energetic ever observed. One event, which began in 2006, reached record brightness (*pink*), beaten by another in 2009 (*orange*). But those died off relatively fast. Another one, from 2007, did not peak quite as high but released the most energy overall (*yellow*). It was the first example of a new type of explosion believed to occur in very massive stars [*see box on next two pages*].



SOURCE: AVISHAY GAL-YAM

In matter that is hot enough, energetic particles such as nuclei and electrons emit very powerful light—photons so energetic that they are in the gamma-ray spectrum. Because of Albert Einstein's famous equation relating mass and energy, $E = mc^2$, two very energetic photons can, if they collide, spontaneously convert into pairs of other particles; specifically, they can transform into a pair that consists of an electron and its antiparticle, the positron. Most of the energy of the photons thus gets locked up in the form of matter. Consequently, electrons and positrons exert much lower pressure than the photons they originated from: they are deadweight. If the core of a very massive star reaches these conditions, its pressure suddenly falls, almost as if the star had a release valve. Before, pressure was what kept the star from collapsing under its own weight; now the core becomes unstable and begins to rapidly contract.

As density shoots up, it ignites the fusion of oxygen. Because the threshold to fusing oxygen is crossed in a collapsing core rather than in a stable one, the ignition is explosive: fusion releases nuclear energy that heats the material further, which in turn speeds up the fusion, in a "runaway" reaction. The star can burn so much oxygen in such a short time—mere minutes—that the energy it releases is larger than the star's entire gravitational energy. Thus, whereas typical supernovae leave behind charred remains such as a neutron star or a black hole, in this type of explosion the object completely obliterates itself. All that is left is a fast-expanding cloud, much of it made of elements that were synthesized in the fury of the deflagration.

The theorists predicted that this type of event—called a pair-instability supernova because it destabilizes the star through the production of electron-positron pairs—would form a huge amount of nickel 56 in addition to other relatively heavy elements. Nickel 56 is an isotope with a tightly bound nucleus that nonetheless is radioactive, ultimately producing nonradioactive iron. If this scenario occurred in the precursor of SN 2006gy, we thought, the decay of nickel 56 might explain the supernova's intense luminosity.

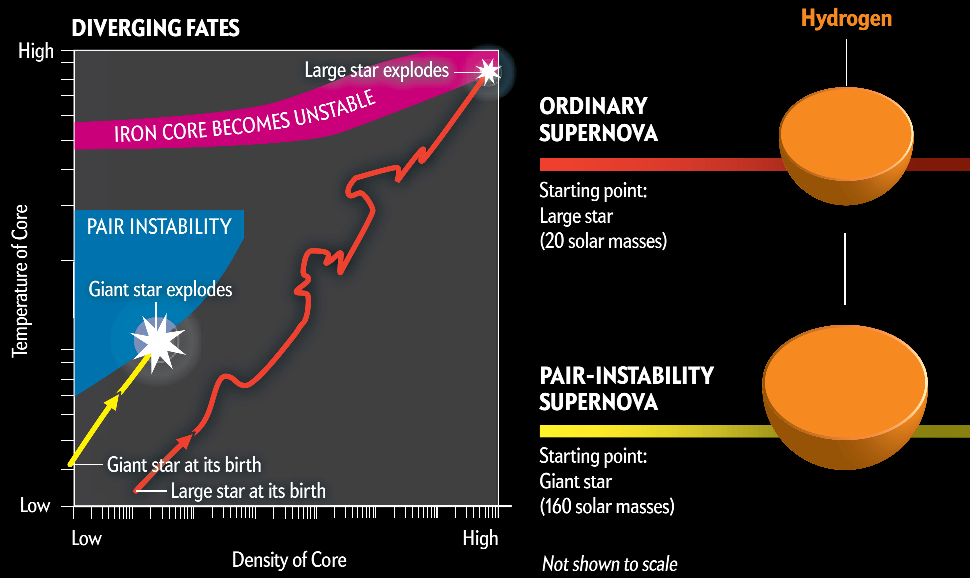
Although the three astrophysicists' theory was correct, for decades common wisdom was that their hypothetical process would not actually take place in nature. Theorists who work on the formation and evolution of stellar bodies thought that such massive stars should not form at all, at least not in the present-day universe. And even if they did form, they would drive such strong stellar winds that they would rapidly lose most of their mass, leaving them unable to form cores massive enough to reach pair instability. The situation was different less than a billion years after the big bang. Then, the first stars might have been massive enough to explode as pair-instability supernovae. Perhaps.

Meanwhile the new record-smashing supernova, SN 2006gy, became a hit among astronomers, spurring more observational and theoretical studies. Ironically, even though SN 2006gy prompted us and others in the supernova community to reconsider the pair-instability model, this particular event did not, in the end, seem to have the right signature for nickel radioactivity—namely, a specific way the light dimmed with time. In a pair-instability explosion, most of the light should come not from the blast itself but from nickel 56 and the other radioactive isotopes it forges. Radioactivity is a well-studied process in which decay proceeds at a predictable, gradual rate. But SN 2006gy, after being bright for many months, quite suddenly disappeared, too quickly to have been powered by radioactivity. It was likely not a pair-instability supernova after all, and the other option we had considered—that the event's unusual brightness originated from

SUPERNOVAE COMPARED

How Large Stars Die

Stars forge new elements by nuclear fusion, which is what makes them shine. As a star ages, its core gets hotter and denser (*graph*) and produces heavier and heavier elements, which tend to form onionlike layers (*diagram*). A relatively heavy star, such as one of 20 solar masses (*red in graph and diagram*), eventually becomes dense enough that it collapses, spewing out large amounts of energy and much of its mass. But a very heavy star, say, 160 solar masses (*yellow*), annihilates itself sooner in a recently discovered, even mightier type of blast.



SOURCE: MODIFIED FROM "THE MOST MASSIVE CORE-COLLAPSE SUPERNOVA PROGENITORS," BY R. WALDMAN, IN *ASTROPHYSICAL JOURNAL*, VOL. 685; OCTOBER 1, 2008 (*graph*)

a shock wave—became the accepted explanation. Still, the near miss had put me on the alert for signs of pair-instability events.

THE REAL THING?

A FEW MONTHS AFTER our lucky break with the Hawaiian clouds, I went to Colorado on vacation. Soon, however, I was interrupted by an e-mail from Peter Nugent of Lawrence Berkeley National Laboratory. Nugent and I had just started a "practice run" for a big supernova search we had been planning. Now he sent me a supernova with a weird spectrum. I had never seen its like before.

Because atoms of each element in nature absorb and emit light at particular wavelengths, the spectrum of an astronomical source provides information about the chemical composition of the material emitting the light. The spectrum of Nugent's object—SN 2007bi—suggested that the elements that composed it were present in unusual proportions and that it was extremely hot.

After I got back to Caltech, I continued to track the evolution of this event. It emitted about 10 times more light than the typical supernova. And the amount of light declined very slowly: this source just refused to fade away, as days turned into weeks and weeks into months. I became more and more convinced that this was finally an example of a pair-instability supernova. It took more than a year before it finally disappeared from view. But I needed more data to be truly sure of my interpretation.

During 2007 and 2008 several collaborators and I continued to observe SN 2007bi using telescopes at Caltech's Palomar Observatory. As the light from this explosion finally grew fainter, about a year after we discovered it, I asked my Caltech colleagues Richard Ellis and Kulkarni to observe it with the large telescopes at Keck—promising in my e-mails that this was "the real deal."

In the meantime, I moved to Israel with my family and took up my current job at the Weizmann Institute of Science in Rehovot. In August 2008 Kulkarni and his graduate student Mansi Kasliwal sent me the latest spectrum for SN 2007bi. When I did a first, rough analysis, I could not believe what I saw. I analyzed the spectrum over and over, but the answer was the same: this explosion synthesized a staggering amount of nickel 56: between five and seven times the entire mass of our sun. It was 10 times more than we or anyone else had ever seen before—and just what you expect from a pair-instability supernova explosion. That night I paced back and forth in my apartment, thinking about this finding and its implications. When my wife gave me a strange look and asked what was going on, I said, "I think we've made a great discovery."

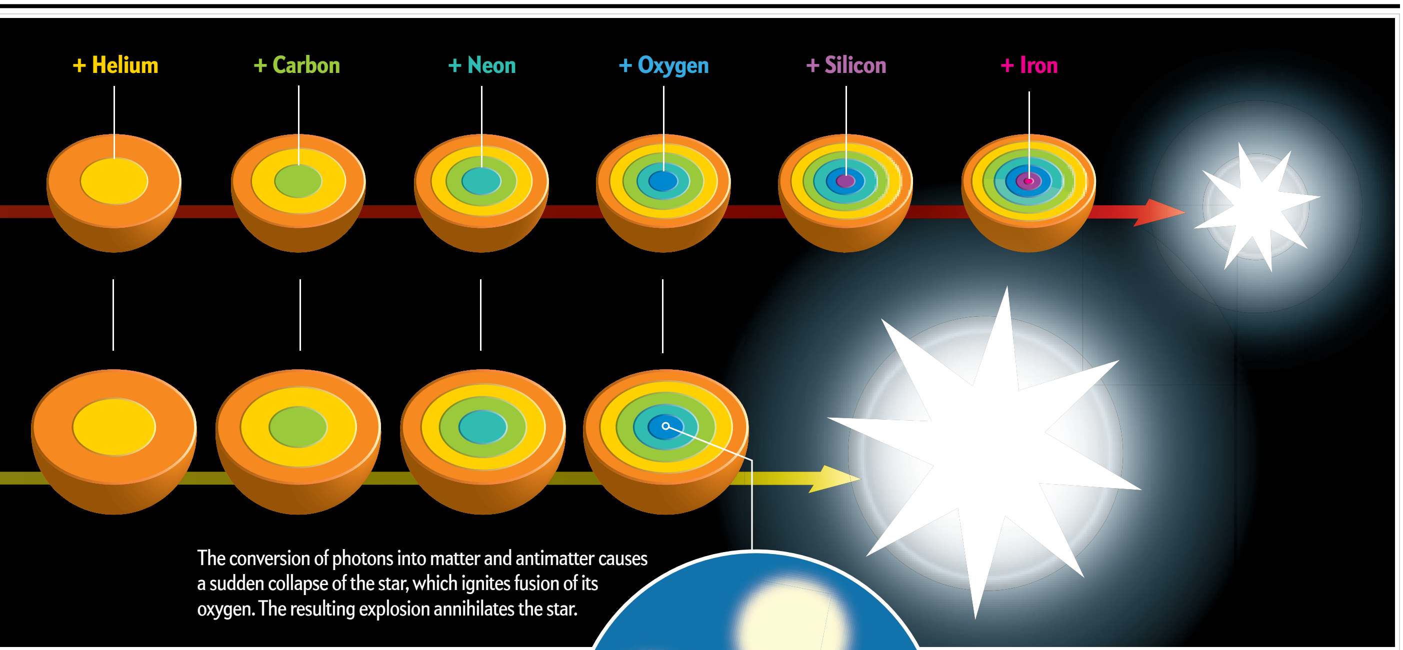
In late 2008 I traveled to Garching, Germany, to work with Paolo Mazzali at the Max Planck Institute for Astrophysics. Mazzali is a world expert in quantitative analysis of supernova spectra, so he could test the results of my rough analysis. He also had additional useful data he had obtained with another large instrument, the European Southern Observatory's Very Large Telescope in Chile. We sat together in his office as Mazzali ran his code. Yes! The results were consistent with my previous analyses: many solar masses of nickel 56, and a relative abundance of elements matching the predictions of pair-instability models.

DOUBLE TAKE

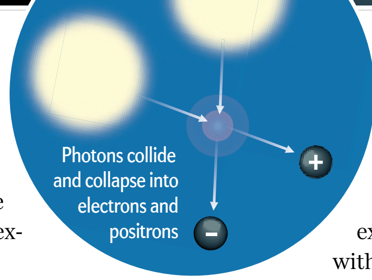
ALTHOUGH I WAS PRETTY CONFIDENT that we had identified a pair-instability supernova, when I returned to Israel I set the data aside for a few months while I was busy on another project involving the supernova that had set me on this journey in the first place: SN 2005gl. When Fox, Leonard and I found its putative progenitor star in late 2005, we could not be positive that it was indeed a single entity rather than a cluster of stars. Now, three years later, the supernova had disappeared, and I realized we could do a simple test: if our candidate was not the star that had blown up, it would still be there. Leonard and I returned to the Hubble to check.

By the end of 2008 we were finally sure: the star had disappeared. The progenitor of SN 2005gl was indeed very luminous and probably quite massive—a twin of Eta Carinae, one of the heftiest blue giants in our own galaxy.

Thus, the prevailing theory of hypergiant stars—that they



The conversion of photons into matter and antimatter causes a sudden collapse of the star, which ignites fusion of its oxygen. The resulting explosion annihilates the star.



lose most of their mass before they explode—was wrong at least in this case. Some very luminous and massive stars do exist and explode before they lose all of their mass. And if the mass-loss theory was wrong, maybe some hypergiant stars still exist that can eventually explode as pair-instability supernovae.

Now I was ready to revisit SN 2007bi and to look for more conclusive evidence of a pair-instability explosion. A team of collaborators and I tested it in every way we could think of. We analyzed its spectra in detail and how its light evolved in time. We compared old models of stellar explosion and new ones. Near the end of 2009 all the evidence converged into a single conclusion: the most logical, almost inescapable way to explain SN 2007bi was that it was a pair-instability supernova. After more than two years of study, it was finally time to start publishing our results.

We have now collected three more events that are strong candidates for pair-instability supernovae. Overall, they appear to be exceedingly rare—constituting only one out of 100,000 supernovae—and to require a star of at least 140 solar masses and perhaps as many as 200. But they are huge factories of the elements, and they produce the most energetic explosions known to science. They might even deserve the name "hypernovae."

Perhaps the most fascinating aspect of this new type of supernova is that it gives us a glimpse into the early universe. The very first stars to light up, some 100 million years after the big bang, would have measured upward of 100 solar masses and maybe as much as 1,000 [see "The First Stars in the Universe," by Richard B. Larson and Volker Bromm; Scientific American, December 2001]. Some of those behemoths probably exploded via a pair-instability mechanism. Thus, the distant cousins of some of today's supernovae may have been the first explosions to seed the universe with heavier elements, thereby shaping the stars and planets that followed them—including our sun and Earth.

Not only do our observations suggest a novel way for stars to blow up, they also mean that the modern universe, contrary to earlier views, probably is sprinkled with hypergiant stars. Growth to extraordinary sizes for primordial stars was possible only in an environment made almost exclusively of hydrogen and helium. "Pollution" with the products of nuclear fusion then put a choke hold on stellar accretion: in the presence of heavier elements, stars collapse faster and thus ignite sooner, blowing off any residual gas around them before they can grow too heavy. But clearly, the heavier elements are less of a brake on stellar growth than astrophysicists used to believe.

The supernova survey Nugent and I began to plan in 2007 is now up and running: it is called the Palomar Transient Factory. As part of that project, we are searching for additional examples of pair-instability explosions; in fact, it enabled us to find one of our latest candidate events, which looks very much like SN 2007bi. As data accumulate, our understanding of these explosions and how they contribute to making the heavy elements in the universe deepens. Future instruments, such as NASA's next-generation observatory, the James Webb Space Telescope, will probably be able to detect very distant pair-instability explosions. Perhaps one day they will reveal the explosive deaths of the first stars to have ever formed in our universe. SA

MORE TO EXPLORE

How to Blow Up a Star. Wolfgang Hillebrandt, Hans-Thomas Janka and Ewald Müller in *Scientific American,* Vol. 295, No. 4, pages 42–49; October 2006.

A Massive Hypergiant Star as the Progenitor of the Supernova SN 2005gl. A. Gal-Yam and D. C. Leonard in *Nature,* Vol. 458, pages 865–867; April 16, 2009.

Supernova 2007bi as a Pair-Instability Explosion. A. Gal-Yam et al. in *Nature,* Vol. 462, pages 624–627; December 3, 2009.

SCIENTIFIC AMERICAN ONLINE
See an interactive animation on stellar explosions at ScientificAmerican.com/jun2012/gal-yam