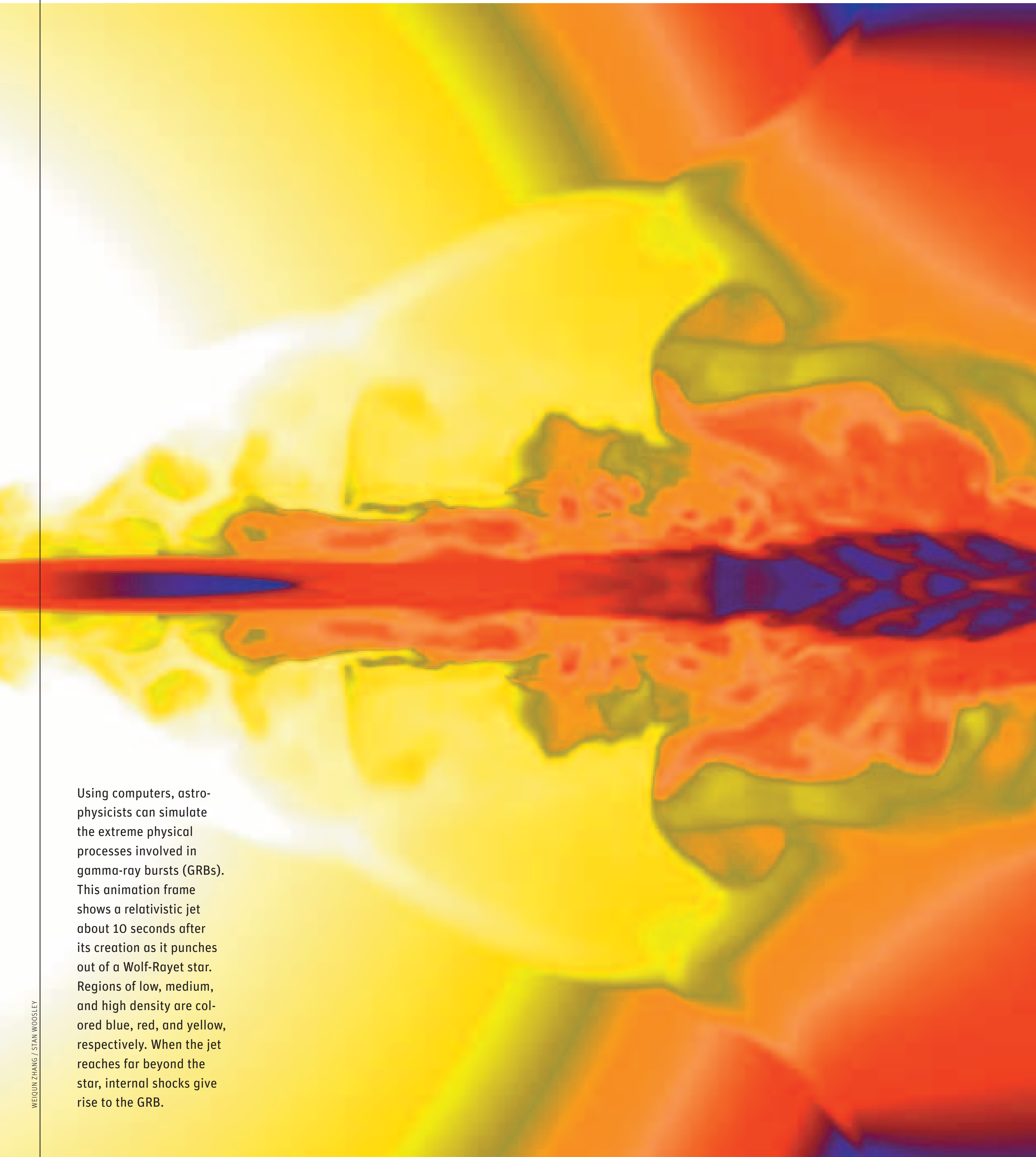

WEIQUN ZHANG / STAN WOOSLEY

Using computers, astrophysicists can simulate the extreme physical processes involved in gamma-ray bursts (GRBs). This animation frame shows a relativistic jet about 10 seconds after its creation as it punches out of a Wolf-Rayet star. Regions of low, medium, and high density are colored blue, red, and yellow, respectively. When the jet reaches far beyond the star, internal shocks give rise to the GRB.

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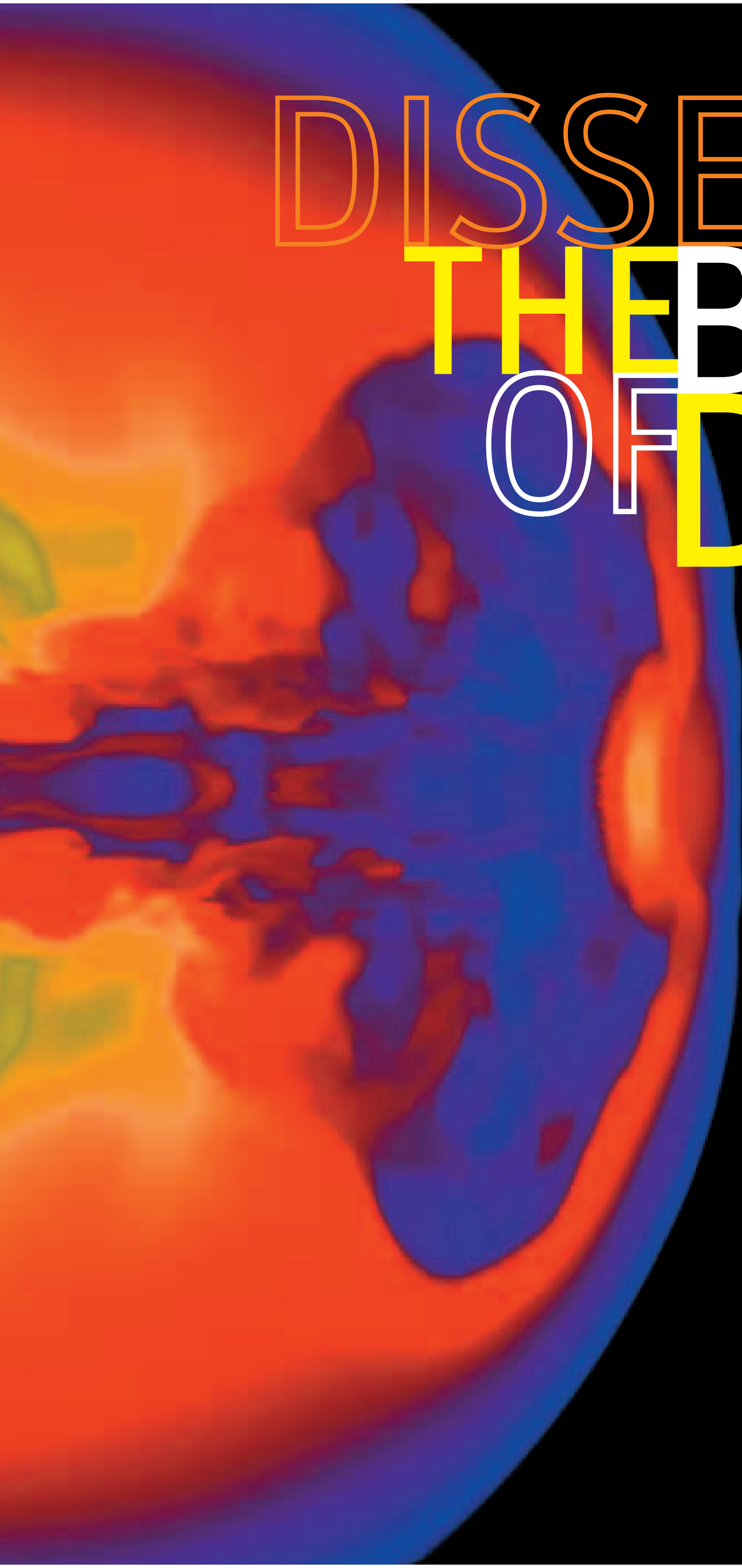

DISSECTING THE BURSTS OF DOOM

By Robert Naeye

FOR YEARS gamma-ray bursts (GRBs) have had a nasty reputation. News accounts frequently describe them as "the most powerful explosions since the Big Bang," "the birth cries of black holes," and "death stars" or "death rays" that wreak mayhem and devastation throughout the universe.

The media can hardly be blamed for hyperbole. GRBs result from tantrums of stupendous violence, when Mother Nature crams the fury of billions of Suns into pulses of high-energy radiation that generally last mere seconds but shine brightly across the universe.

GRBs have befuddled astronomers ever since US surveillance satellites discovered them serendipitously in the 1960s while looking for Soviet clandestine nuclear tests. What could possibly unleash such unmitigated ferocity in such fleeting spurts of time? Bursts appeared suddenly from random directions and quickly vanished, leaving astronomers with nothing to follow up. With very little data to constrain imaginations, theories soon outnumbered detected bursts.

But with a new generation of satellites, elaborate computer models, and the power of the scientific mind, the field is witnessing a harmonic convergence of theory and observation. It would be wildly presumptuous to claim that astronomers have attained a complete understanding of GRBs, but they are closing in on all sides.

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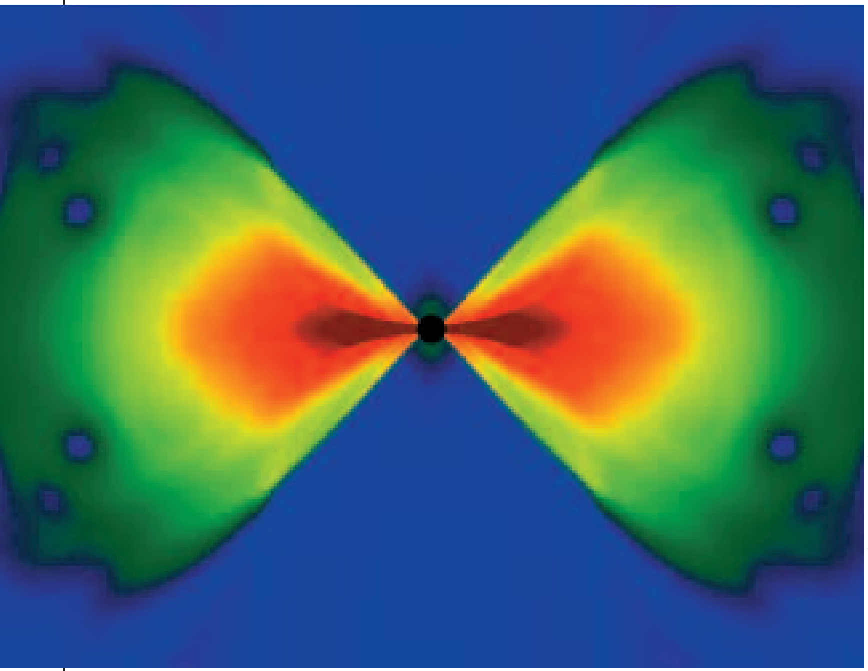


ANDREW MACFADYEN / WEIQUN ZHANG / STAN WOOSLEY

This animation frame zooms in close to the black hole and accretion disk that form a GRB's central engine. The black hole lies at the center; the accretion disk, in cross section, is the brown and red region to the left and right of the hole.

A Brief History of GRBs

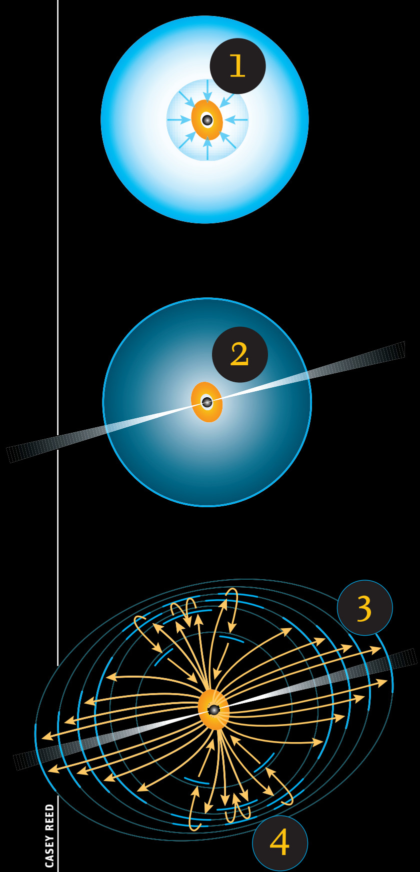
A breakthrough occurred in 1997, when the Italian-Dutch satellite BeppoSAX started to zero in on burst locations quickly enough so that other telescopes could catch the fading afterglows and pinpoint their locations. The afterglows were always seen in active star-forming regions of extremely distant, faint galaxies. This critical information established that GRBs were incredibly powerful explosions related to massive stars, which have such short lives that they can't wander far from their birthplace.

Then on April 25, 1998, BeppoSAX picked up an unusually weak burst (named GRB 980425 for its date) in a galaxy only 120 million light-years from Earth. Just 2½ days later, astronomers noticed a supernova (SN 1998bw) emerging at the same location — firmly establishing that GRBs come from exploding massive stars. Other such pairings followed, bolstering the GRB-supernova connection.

Only a few GRBs have erupted close enough to allow astronomers to see the associated supernova. But in each case, the supernova has been a Type Ic, meaning its spectrum shows no hydrogen or helium. This finding strongly supports predictions that GRB progenitors are Wolf-Rayet stars: hot, massive stars that have blown off their outer hydrogen- and helium-rich layers in fierce stellar winds.

In 1999 a clear winner emerged out of the hundreds of

Anatomy of a Collapsar-Generated GRB



1. THE CENTRAL ENGINE FORMS
Material from a collapsing Wolf-Rayet star falls inward, settling into an accretion disk around a central black hole containing 3 to 4 solar masses. The black hole rotates faster than the accretion disk, so magnetic-field lines are wound up, collimating two jets that zoom away along the star's rotation axis. The engine must operate for at least 10 seconds and hold the direction of the jet steady to within 5° for the jet to reach the star's surface.

2. RELETIVISTIC JETS
Twin relativistic jets shoot away from the central engine, reaching 99.999% the speed of light outside the star. In the collapsar model, each jet contains roughly 1 Earth mass of protons and neutrons, but 10 to 20 times more effective mass in the form of radiation (due to $E = mc^2$). A jet triggers the GRB, but it's not efficient enough to blow up the star. If the jet picks up too much matter on the way out, it slows the outflow and reduces the energy, perhaps resulting in an X-ray flash rather than a GRB. Some astronomers think the jets are beams of pure electromagnetic energy.

3. BROADER OUTFLOW OF WIND
The accretion disk blows off a wind of heavy elements that races outward at about 10% the speed of light before decelerating as it rams into stellar material. This wind provides the kinetic energy that blows the star apart as a Type Ic supernova, and it contains about 10 times more total energy than the jets. The outflow synthesizes about 0.5 solar mass of nickel-56, whose radioactive decay provides most of the supernova's early light emission.

4. FALLBACK DEBRIS
Oxygen-rich gas is ejected along the star's equator. But this material has insufficient velocity to escape, so it eventually falls back onto the black hole and reignites the central engine minutes to hours after the initial GRB. This activity shows up as powerful X-ray flares in Swift data.

S&T: CASEY REED

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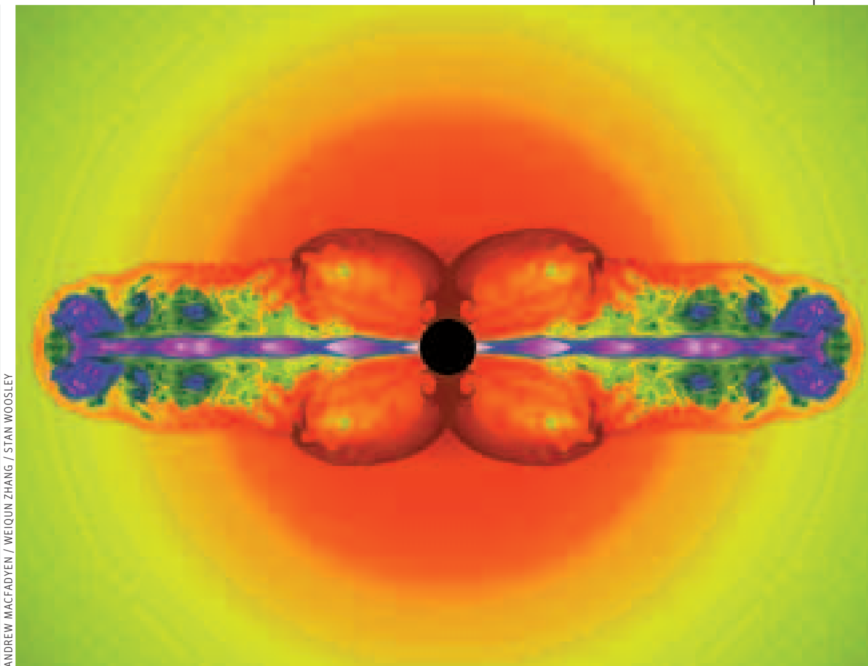
competing theories attempting to explain GRBs: the "collapsar" model developed by Stan Woosley (University of California, Santa Cruz) and his graduate student Andrew MacFadyen (now at the Institute for Advanced Study). Their computer simulations showed what happens when the rapidly rotating core of a Wolf-Rayet star runs out of nuclear fuel and collapses, forming a black hole. They found that infalling stellar material forms a tiny, dense accretion disk that feeds the black hole for a few tens of seconds. Twisted magnetic field lines channel about an Earth's worth of ejecta and a huge amount of electromagnetic energy into two jets that burrow through the dying star along its rotation axis at relativistic velocities very close to the speed of light.

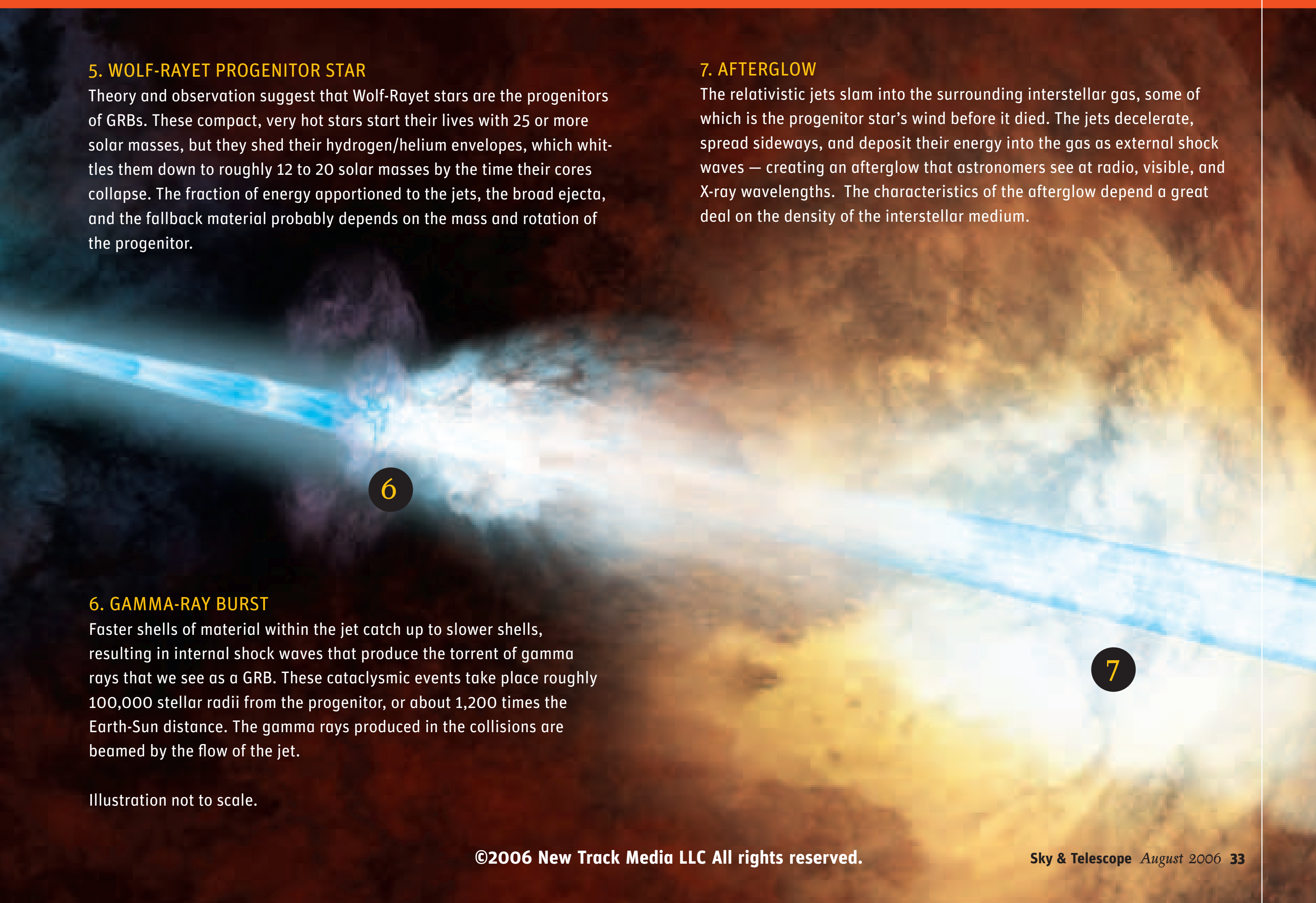
Details of how the GRB itself is generated remain controversial. In the "internal shock" model developed by Martin Rees (Cambridge University, England), Peter Mészáros (Penn State University), Tsvi Piran (Hebrew University of Jerusalem, Israel), and others, it could come from shells of jet ejecta colliding with one another far outside the dying star.

The collapsar model implies that we see only those GRBs whose jets happen to point at Earth. "It means that for every GRB we see, there are several hundred we don't," says MacFadyen. "It also means that the total energy you need to form a burst is about a hundred times smaller, since we previously assumed they were emitting energy in



ANDREW MACFADYEN / WEIQUN ZHANG / STAN WOOSLEY

The collapsar mechanism spawns a relativistic jet, simulated in this frame. The intense turbulence in and around the jet is clearly visible. The jet is mostly electromagnetic energy, with surprisingly little matter entrained within it.



5. WOLF-RAYET PROGENITOR STAR

Theory and observation suggest that Wolf-Rayet stars are the progenitors of GRBs. These compact, very hot stars start their lives with 25 or more solar masses, but they shed their hydrogen/helium envelopes, which whittles them down to roughly 12 to 20 solar masses by the time their cores collapse. The fraction of energy apportioned to the jets, the broad ejecta, and the fallback material probably depends on the mass and rotation of the progenitor.

6. GAMMA-RAY BURST

Faster shells of material within the jet catch up to slower shells, resulting in internal shock waves that produce the torrent of gamma rays that we see as a GRB. These cataclysmic events take place roughly 100,000 stellar radii from the progenitor, or about 1,200 times the Earth-Sun distance. The gamma rays produced in the collisions are beamed by the flow of the jet.

7. AFTERGLOW

The relativistic jets slam into the surrounding interstellar gas, some of which is the progenitor star's wind before it died. The jets decelerate, spread sideways, and deposit their energy into the gas as external shock waves — creating an afterglow that astronomers see at radio, visible, and X-ray wavelengths. The characteristics of the afterglow depend a great deal on the density of the interstellar medium.

Illustration not to scale.

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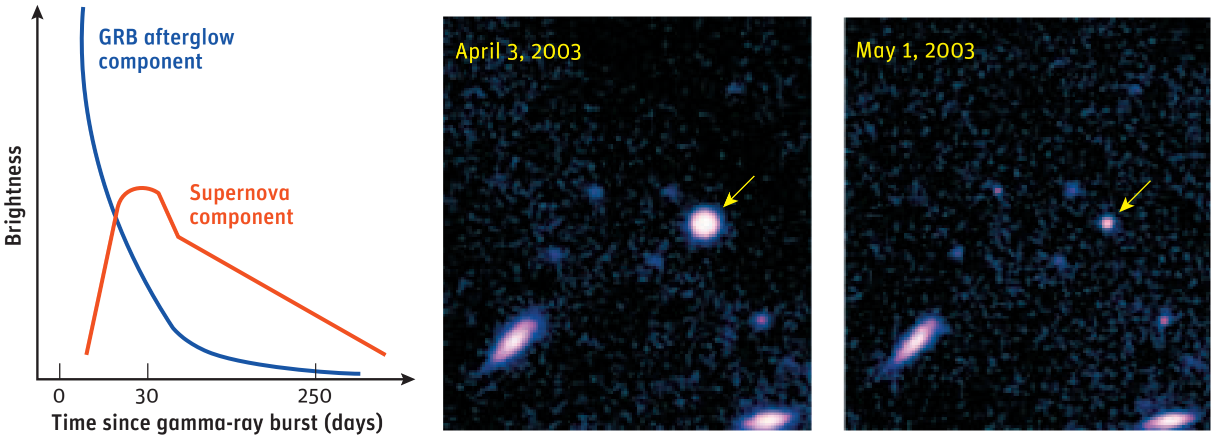


SOURCE: JOSHUA BLOOM

EUROPEAN SOUTHERN OBSERVATORY (2)

Left: This model light curve shows how a GRB's fading afterglow dominates the early light emission, but then becomes overwhelmed as the underlying supernova brightens. *Center and right:* These images show the fading visible-light emission of the March 29, 2003 GRB, which was associated with a supernova.

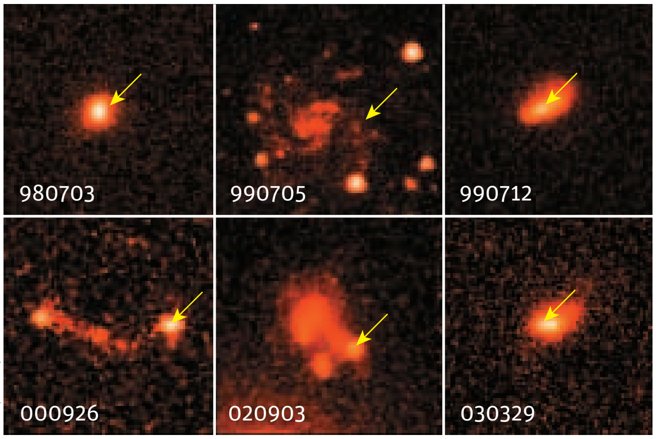
all directions. They've come down in energy, but they're still extremely energetic."

The properties of GRB afterglows at X-ray, visible, and radio wavelengths match predictions of the collapsar model. The afterglows tend to fade slowly for several days before suddenly falling off rapidly, indicating that relativistic jets only a few degrees wide are violently decelerating and depositing their energy as they plow through interstellar gas.

By 2000, astronomers had also established that GRBs fall into two broad classes: long bursts of relatively "soft" (low-energy) gamma-ray emission lasting from several seconds to several minutes, and short, "hard" bursts lasting for 0.01 second to 2 or 3 seconds (*S&T:* March 2004, page 32). The long bursts were clearly associated with the deaths of massive stars. But the short bursts — for which no afterglows had yet been observed — remained an enigma.

It also became apparent that perhaps one-third of long bursts display such soft emission that their energy peaks in the lower-energy, X-ray part of the spectrum. Astronomers started calling these events "X-ray flashes" (XRFs) rather than GRBs.

Despite these breakthroughs, by 2004 astronomers were still left with major questions. How many supernovae are associated with GRBs? How has the rate and energy of



NASA / STSCI / ANDREW FRUCHTER ET AL.

A recent Hubble Space Telescope survey of GRB host galaxies revealed a remarkable fact: GRBs (whose locations are marked by arrows) almost always explode in irregular dwarf galaxies. Such galaxies usually have few "metals" (elements heavier than hydrogen and helium), which indicates that GRB progenitor stars are also low in metallicity.

GRBs changed over cosmic history? Are GRBs and XRFs basically the same thing? And what causes the short bursts? To answer these questions, astronomers needed better data.

The Swift Era

Enter NASA's High Energy Transient Explorer 2 (HETE-2) and Swift satellites, launched in 2000 and 2004, respectively. These relatively low-cost missions have led to the current frenzy of activity, with several new GRB research papers being posted daily on the Internet.

By living up to its name, Swift has lofted GRB research to new heights with its ability to slew rapidly to a burst's coordinates and conduct immediate follow-up observations with ultraviolet/optical and X-ray telescopes (January issue, page 48). Swift catches about two bursts per week, alerting hundreds of professional and amateur astronomers within minutes (often ringing their cell phones in the middle of the night). This enables rapid follow-up by observatories around and above the world.

Thanks to Swift, astronomers have made a series of remarkable discoveries:

• Swift has caught several record-breaking high-redshift GRBs (redshift is a measure of how much an object's light has been stretched by cosmic expansion), including an extremely powerful burst on September 4, 2005, at a redshift of 6.29 — emitted only 900 million years after the Big Bang. This is almost as far away as the most distant known quasars and galaxies. More remote bursts are sure to follow, perhaps even to redshifts greater than 10. Such extremely distant bursts provide a golden opportunity to probe conditions in the young universe and the nature of early stars.

• Swift has discovered that about a third of long GRBs exhibit powerful X-ray flares minutes to hours after the main burst (*S&T:* September 2005, page 20). Most astronomers interpret these outbursts as resulting from ejected material falling back onto the black hole. The GRB at redshift 6.29 exhibited particularly intense flares more than an hour after the burst, activity typical of the most distant bursts.

• Swift and other satellites caught a long GRB on February 18, 2006 (June issue, page 20). Located in a galaxy "only" 470 million light-years away, it is the second-closest long burst with a measured distance (after GRB 980425). GRB 060218 lasted 33 minutes, longer than any previously seen burst. It too was associated with a Type Ic supernova (SN

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2006aj). But astronomers quickly noted that the burst was extremely soft, and most are now calling it an X-ray flash rather than a GRB. Despite the event's longevity, its total emitted energy was very weak for a long burst. As Swift lead scientist Neil Gehrels (NASA/Goddard Space Flight Center) says, "It is a very different burst than any we have seen."

Some astronomers suspect that the star's core collapsed into a fast-spinning neutron star rather than a black hole, and instead of producing a narrow beam of highly relativistic ejecta, it produced a broad outflow of mildly relativistic ejecta. This event may signify a GRB that nearly failed — where the ejecta barely managed to punch out of the star.

Nearby GRBs like 980425 and 060218 pack only 1% to 10% the total energy of high-redshift GRBs, indicating some important difference in the progenitor stars. In fact, Swift and other satellites lack the sensitivity to detect these low-luminosity bursts beyond a billion light-years. But since subenergetic bursts dominate the local population, they may constitute the majority of GRBs in the universe.

Location, Location, Location

While Swift continues to localize new GRBs, astronomers are attacking the remaining mysteries on multiple fronts. When a GRB jet rams into interstellar gas, it injects huge amounts of energy into the material, generating a bright radio source regardless of the jet's direction. SN 1998bw in particular was a powerful radio emitter. Alicia Soderberg (Caltech) and her colleagues are targeting Type Ic supernovae and their close cousins, Type Ib supernovae, which have helium in their spectra. The team is using the Very Large Array in New Mexico to see how many of these supernovae might be associated with off-axis GRBs (those whose jets don't point at Earth). But despite examining about 150 supernovae, they have yet to find a single radio source indicating an off-axis GRB. This implies that less than 1% of all Type Ib/c supernovae produce relativistic ejecta. "GRBs are intrinsically rare events, so we know it takes a very special supernova to produce one," says Soderberg.

Astronomers are also gaining insight into the nature of GRB progenitors by studying their host galaxies, which almost always turn out to be irregular dwarf galaxies that are vigorously forming massive stars. Since dwarf galaxies usually have very low concentrations of elements heavier than hydrogen and helium ("metals" in astronomy parlance), these results strongly suggest that GRB progenitor stars have low metallicity — another prediction of the collapsar model.

Using GRBs for Cosmology

By Andrew Samuel Friedman

Taking on Einstein has become a cottage industry for scientists. At the January 2006 American Astronomical Society meeting, Bradley Schaefer (Louisiana State University) reported that he had used long-duration gamma-ray bursts (GRBs) as standard candles (distance indicators of known luminosity) to measure the universe's expansion history. Schaefer boldly concluded that the dark energy responsible for accelerating the expansion had changed in strength over time. This result called into question the constancy of one of Einstein's most storied concepts, the cosmological constant (June issue, page 22). Schaefer's effort exemplifies the excitement and controversy surrounding the emerging field of GRB cosmology.

For the past decade, two competing teams have used supernovae of the Type Ia class as standard candles. With their extraordinary luminosities, these white-dwarf explosions can be seen across billions of light-years, which allowed the teams to make their remarkable 1998 discovery that the universe's expansion is accelerating. This surprising result resurrected Einstein's cosmological constant.

Could GRB standard candles be the new game in town? GRBs are much more luminous than Type Ia supernovae, so they can be seen further back in time. But they suffer from a host of problems. In contrast to Type Ia supernovae, which have relatively uniform properties, GRB luminosities vary by a factor up to a million when not adjusted for beaming. To correct for this wide variation, astronomers must correlate several observed properties, such as the burst's peak gamma-ray energy and the time when the afterglow exhibits a sharp decrease in brightness. Astronomers have developed several other GRB standardization methods, but each has its own pitfalls that could undermine accurate distance estimates. This is of particular concern when different methods are combined, as in Schaefer's analysis.

While hundreds of Type Ia supernovae have measured distances, only about 20 GRBs can be placed on a reliable Hubble diagram — a graph that plots distance versus redshift (Schaefer used about 50). Swift, combined with other satellites, is contributing some of the higher-redshift bursts that most constrain the current Hubble diagram. But there haven't been enough GRBs nearby to calibrate their luminosities. This problem has long been resolved for Type Ia supernovae because they have been well studied in nearby galaxies, some with independent distance measurements from Cepheid variable stars. Unfortunately, the paltry few nearby GRBs have exhibited low energies and strange properties, suggesting that their progenitors differ from their more-distant cousins. Without local calibration, GRBs have limited utility for tracking dark energy's behavior through time.

Still, since gamma rays penetrate dust and GRB spectra are simpler than supernova spectra, GRB standard candles could avoid some of the problems that have plagued Type Ia supernova distance estimates. Moreover, since GRBs can be detected at much greater distances, astronomers could, in principle, map the expansion history out to a time when the universe was less than a billion years old. But the early universe's expansion was dominated by matter's gravitational attraction, not dark energy's repulsion — which took over only within the past few billion years. This also limits GRBs' usefulness for studying dark energy.

Rather than pointing to the evolution of dark energy's strength, Schaefer's results are more convincingly interpreted as indirect evidence for the evolution of GRB luminosity, with more-distant GRBs yielding higher-energy explosions (though this was already suspected). Our knowledge of GRBs is not yet mature enough to draw conclusions on dark energy's time variation. Although GRBs may not have Einstein turning over in his grave, it is safe to say that if he were alive today, the brightest explosions in the universe would certainly have piqued his interest.

Harvard PhD student ANDREW SAMUEL FRIEDMAN'S *research involves developing novel standard candles such as GRBs and supernovae at near-infrared wavelengths as tools to map cosmic expansion history.*

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In a study published in the May 10th online edition of *Nature,* a team led by Andrew Fruchter (Space Telescope Science Institute) used the Hubble Space Telescope to image the host galaxies of 42 long GRBs. Only *one* of the 42 went off in a large, well-formed spiral; the rest exploded in irregular dwarfs. Moreover, the GRBs usually exploded in the brightest region within their galaxy, where the most intense star formation is taking place and where the most massive stars reside. In contrast, the survey found that normal supernovae are evenly divided between spirals and dwarfs. These results reinforce the prevailing view that GRB progenitors are very massive and have low metallicity.

This result is consistent with a study submitted to the *Astrophysical Journal* by Krzysztof Stanek (Ohio State University) and nine colleagues. Stanek's group scrutinized the host galaxies of five of the nearest long GRBs (including XRF 060218), all of which are closer than 2 billion light-years. The team found that all of the galaxies had an oxygen abundance (a proxy for metals more generally) less than 60% of the Sun's, and that the higher the host's metallicity, the lower the burst's energy.

The correlation between GRBs and low metallicity may partially explain why we exist, since GRBs' concentrated beams of high energy would devastate planetary atmospheres up to thousands of light-years away (June issue, page 30). The Milky Way's stars have become highly enriched in metals over 13 billion years of stellar evolution, and even by the time Earth formed 4.6 billion years ago, most stars in our galaxy's disk may have been so metal-rich that GRBs posed a negligible threat to life-bearing planets. Stanek's group concludes, "We can probably cross GRBs off the rather long list of things that could cause humankind to join the dinosaurs on the extinct species list."

Rotation, Rotation, Rotation

The low metallicity of GRB progenitors is not only good news for Earth — it's a vital clue about their nature. As Dale Frail (National Radio Astronomy Observatory) explains, "Metallicity and rotation go hand in hand."

Frail points out a key question in GRB research: How does an exploding massive star decide to partition energy between the relativistic jets and the supernova blast wave, which actually does most of the work of blowing up the star? In the collapsar model, an exploding massive star needs to tap a huge reservoir of rotational energy to produce relativistic jets. Otherwise, it produces a run-of-the-mill supernova or a "failed supernova" — where most of the stellar material falls inward to make a black hole without a spectacular explosion.

Elements heavier than hydrogen and helium have more electrons, which means they get pushed more effectively by the intense radiation pressure of high-mass, luminous stars. As a result, a high-metallicity star produces a more powerful stellar wind, which magnetically brakes the star's rotation. Such a star rotates too slowly to form relativistic jets, so it dies as a normal core-collapse supernova without a GRB.

According to a number of theorists, rotation is such an important parameter in GRBs that it doesn't even matter if a collapsing stellar core makes a black hole. As Joshua Bloom (University of California, Berkeley) explains, "You could just make a neutron star and the energetics still work out." A very rapidly spinning neutron star will turn on a dynamo that amplifies its magnetic field to extraordinary strength, resulting in a magnetar (*S&T:* January 2005, page 34). The explosion can tap this magnetic energy to produce relativistic jets. Black-hole events, however, might lead to more powerful GRBs since the jets can draw from an enormous reservoir of gravitational energy.

In the developing picture, only a rare combination of circumstances will enable a star to produce a GRB, which explains why Soderberg's radio observations are not finding supernovae accompanied by relativistic outflows. A star needs to be massive enough to produce a black hole or a neutron star, it needs to lose its envelope, *and* its core needs to be rotating very fast when it collapses.

These conditions create thorny problems for theorists (but apparently not for nature). For example, a GRB progenitor needs to avoid expanding into a red giant — an almost

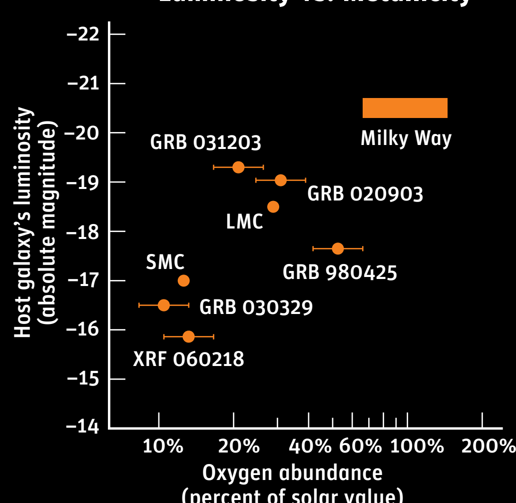
GRB Host Galaxies

Left: **Five of the nearest bursts occurred in galaxies with low metal abundances and low luminosities comparable to those of dwarf irregulars like the Large and Small Magellanic Clouds — the Milky Way's largest satellite galaxies. The Milky Way, for comparison, is depicted as a strip to reflect the range of metallicities in its different regions.**

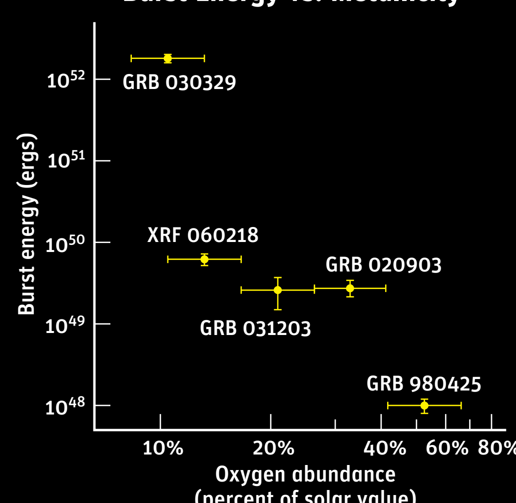
Right: **The higher the metallicity of the host galaxy, the lower the energy of the burst. Together these graphs demonstrate that the progenitor stars of GRBs, and powerful GRBs in particular, are much more likely to form in low-metallicity environments — suggesting that GRBs pose virtually no threat to Earth.**

SOURCE: KRZYSZTOF STANEK (2)

Luminosity vs. Metallicity



Burst Energy vs. Metallicity



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NASA / CXC / SSC / JONATHAN KEOHANE ET AL.

This composite Chandra X-ray Observatory (blue) and Palomar Observatory infrared (red and green) image shows the supernova remnant W49B, located 35,000 light-years away in Aquila. The X-ray emission seems to form a bar, leading some astronomers to propose that it's the remains of GRB jets. The jet moving to the left rammed into interstellar gas, creating the flared region at far left. Other astronomers think this is just an ordinary supernova remnant and argue that few, if any, GRBs have occurred in our galaxy in recent times.

universal phase in stellar evolution, but one that robs a star of angular momentum. But because metal-poor massive stars have relatively weak winds, they should retain a thick, jet-smothering hydrogen envelope by the time the core collapses. Somehow, a GRB progenitor must shed its envelope while retaining a rapid spin.

One obvious way around this problem is the presence of a close binary companion, which can shear off the progenitor's outer envelope. But Woosley and Alexander Heger (Los Alamos National Laboratory) point out that even if the star has no binary companion, there's another way it could lose its envelope. Recent theoretical research indicates that rapidly rotating massive stars mix their internal layers. Such mixing allows a massive star to evolve directly into a Wolf-Rayet star without passing through a red-giant phase, allowing it to maintain its fast rotation.

This model can explain why high-redshift GRBs tend to be so powerful, and why they exhibit pronounced flaring activity. Very-low-metallicity stars shed comparatively little mass in winds, so they retain high masses when they're ready to die. As a result, they produce black holes that can tap a larger reservoir of accreting material and rotational energy to power a jet for a longer time. The collapsar will produce a highly luminous GRB with more infalling material to feed the black hole.

In contrast, the nearby, subenergetic GRBs probably originate from lower-mass progenitors that rotate more slowly, so the collapsar mechanism doesn't have as much accreting mass or rotation energy to power highly relativistic jets. The explosion process channels more of the available energy into the supernova and less into the jets. As evolving stars disperse more metals into their galaxies with the passage of time, the frequency and violence of GRBs should decrease, which agrees with observations.

Mysteries Solved and Unsolved

Theory and observation have converged to form a consistent picture of how, under just the right conditions, massive stars can unleash relativistic jets when they die, and perhaps why some bursts are more powerful than others. But many key issues remain controversial or unresolved. What are the jets made of? What is the typical beaming angle? What actually produces the gamma rays and the X-ray flares? How does our viewing angle affect what we see? How do mass, rotation, metallicity, and binary companions factor in? How many long GRBs are associated with black holes and how many with neutron stars? Is there a continuum of explosion types, or are there sharp classifications? All of these questions ultimately boil down to a question that is simple in principle, but complex in practice: How do massive stars die?

Astronomers are also keenly aware that they have a long way to go to meet the challenge posed by *short* bursts. Whereas Swift has led to a convergence of thinking on long GRBs, its observations have actually muddied the waters for short bursts. As I'll discuss in a future article, no single model can account for their wondrous diversity. They may come from a variety of processes involving black holes and neutron stars.

Even though GRBs are not as powerful as astronomers once thought, they illuminate critical questions about the fates of massive stars and some of the most extreme physical processes in the universe. Best of all, astronomers can marvel at Mother Nature's ingenuity. They may lose sleep from ringing cell phones in the middle of the night, but not from concern over our planet's fate. ✴

Senior editor Robert Naeye *plans to read this article in 10 years to see how much of our current understanding of GRBs holds up.*

To view animations relating to GRBs, visit SkyandTelescope.com/GRB.

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