



A PICTURE LIKE THIS could not have been drawn with any confidence a decade ago, because no one had yet figured out what causes gamma-ray bursts—flashes of high-energy radiation that light up the sky a couple of times a day. Now astronomers think of them as the ultimate stellar swan song. A black hole, created by the implosion of a giant star, sucks in debris and sprays out some of it. A series of shock waves emits radiation.

The Brightest Explosions in the Universe

Every time a gamma-ray burst goes off, a black hole is born

By Neil Gehrels, Luigi Piro and Peter J. T. Leonard

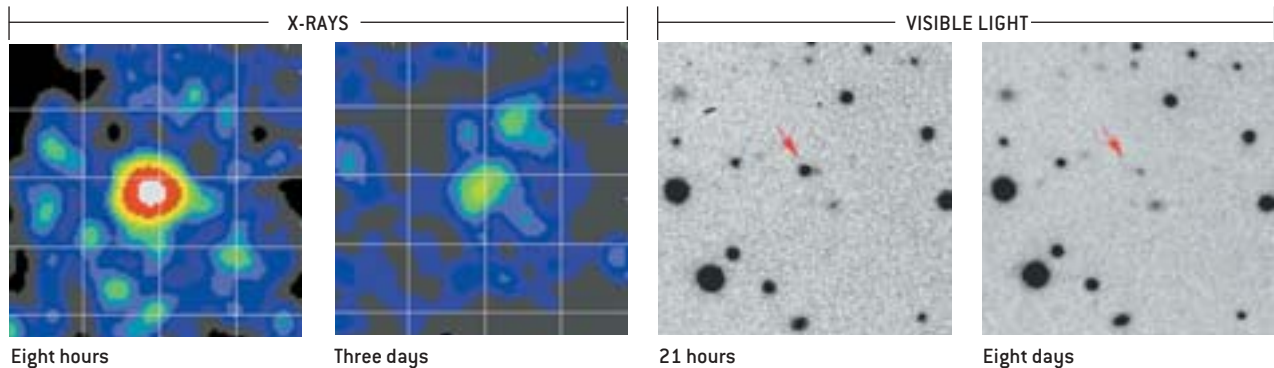
Early in the morning of January 23, 1999, a robotic telescope in New Mexico picked up a faint flash of light in the constellation Corona Borealis. Though just barely visible through binoculars, it turned out to be the most brilliant explosion ever witnessed by humanity. We could see it nine billion light-years away, more than halfway across the observable universe. If the event had instead taken place a few thousand light-years away, it would have been as bright as the midday sun, and it would have dosed Earth with enough radiation to kill off nearly every living thing.

The flash was another of the famous gamma-ray bursts, which in recent decades have been one of astronomy's most intriguing mysteries. The first sighting of a gamma-ray burst (GRB) came on July 2, 1967, from military satellites watching for nuclear tests in space. These cosmic explosions proved to be rather different from the man-made explosions that the

A (VERY) WARM AFTERGLOW

X-RAYS: Eight hours after a burst went off on February 28, 1997, astronomers using the BeppoSAX satellite—including one of the authors [Piro]—saw an x-ray afterglow for the first time. The second image was taken a couple days later, by which time the x-rays had faded by a factor of 20.

VISIBLE LIGHT: A comparably quick reaction by astronomers on La Palma in the Canary Islands allowed the same afterglow to be seen in visible light. Over the next week, the light dimmed to one sixth its original brightness, and as it did so, the surrounding galaxy slowly became apparent.



satellites were designed to detect. For most of the 35 years since then, each new burst merely heightened the puzzlement. Whenever researchers thought they had the explanation, the evidence sent them back to square one.

The monumental discoveries of the past several years have brought astronomers closer to a definitive answer. Before 1997, most of what we knew about GRBs was based on observations from the Burst and Transient Source Experiment (BATSE) onboard the Compton Gamma Ray Observatory. BATSE revealed that two or three GRBs occur somewhere in the observable universe on a typical day. They outshine everything else in the gamma-ray sky. Although each is unique, the bursts fall into one of two rough categories. Bursts that last less than two seconds are “short,” and those that

last longer—the majority—are “long.” The two categories differ spectroscopically, with short bursts having relatively more high-energy gamma rays than long bursts do. The January 1999 burst emitted gamma rays for a minute and a half.

Arguably the most important result from BATSE concerned the distribution of the bursts. They occur isotropically—that is, they are spread evenly over the entire sky. This finding cast doubt on the prevailing wisdom, which held that bursts came from sources within the Milky Way; if they did, the shape of our galaxy, or Earth’s off-center position within it, should have caused them to bunch up in certain areas of the sky. The uniform distribution led most astronomers to conclude that the instruments were picking up some kind of event happening throughout the universe. Unfortunately, gamma

rays alone did not provide enough information to settle the question for sure. Researchers would need to detect radiation from the bursts at other wavelengths. Visible light, for example, could reveal the galaxies in which the bursts took place, allowing their distances to be measured. Attempts were made to detect these burst counterparts, but they proved fruitless.

A BURST OF PROGRESS

THE FIELD TOOK a leap forward in 1996 with the advent of the x-ray spacecraft BeppoSAX, built and operated by the Italian Space Agency with the participation of the Netherlands Space Agency. BeppoSAX was the first satellite to localize GRBs precisely and to discover their x-ray “afterglows.” The afterglow appears when the gamma-ray signal disappears. It persists for days to months, diminishing with time and degrading from x-rays into less potent radiation, including visible light and radio waves. Although BeppoSAX detected afterglows for only long bursts—no counterparts of short bursts have yet been identified—it made follow-up observations possible at last. Given the positional information from BeppoSAX, optical and radio telescopes were able to identify the galaxies in which the GRBs took place. Nearly all lie billions of light-years away, meaning that the bursts must be enormously powerful [see “Gamma-

Overview/*Gamma-Ray Bursts*

- For three decades, the study of gamma-ray bursts was stuck in first gear—astronomers couldn’t settle on even a sketchy picture of what sets off these cosmic fireworks.
- Over the past five years, however, observations have revealed that bursts are the birth throes of black holes. Most of the holes are probably created when a massive star collapses, releasing a pulse of radiation that can be seen billions of light-years away.
- Now the research has shifted into second gear—fleshing out the theory and probing subtle riddles, especially the bursts’ incredible diversity.

MARK A. GARLICK (preceding pages); ENRICO COSTA (Institute of Space Astrophysics and Cosmic Physics, CNR) AND THE BEPPoSAX TEAM (left); PAUL J. GROOT (University of Amsterdam) (right)

Ray Bursts,” by Gerald J. Fishman and Dieter H. Hartmann; SCIENTIFIC AMERICAN, July 1997]. Extreme energies, in turn, call for extreme causes, and researchers began to associate GRBs with the most extreme objects they knew of: black holes.

Among the first GRBs pinpointed by BeppoSAX was GRB970508, so named because it occurred on May 8, 1997. Radio observations of its afterglow provided an essential clue. The glow varied erratically by roughly a factor of two during the first three weeks, after which it stabilized and then began to diminish. The large variations probably had nothing to do with the burst source itself; rather they involved the propagation of the afterglow light through space. Just as Earth’s atmosphere causes visible starlight to twinkle, interstellar plasma causes radio waves to scintillate. For this process to be visible, the source must be so small and far away that it appears to us as a mere point. Planets do not twinkle, because, being fairly nearby, they look like disks, not points.

Therefore, if GRB970508 was scintillating at radio wavelengths and then stopped, its source must have grown from a mere point to a discernible disk. “Discernible” in this case means a few light-weeks across. To reach that size, the source must have been expanding at a considerable rate—close to the speed of light.

The BeppoSAX and follow-up observations have transformed astronomers’ view of GRBs. The old concept of a sudden release of energy concentrated in a few brief seconds has been discarded. Indeed, even the term “afterglow” is now recognized as misleading: the energy radiated during both phases is comparable. The spectrum of the afterglow is characteristic of electrons moving in a magnetic field at or very close to the speed of light.

The January 1999 burst (GRB990123) was instrumental in demonstrating the immense power of the bursts. If the burst radiated its energy equally in all directions, it must have had a luminosity of a few times 10^{45} watts, which is 10^{19} times as bright as our sun. Although the other well-known type of cosmic cataclysm, a supernova explosion, releases almost as

much energy, most of that energy escapes as neutrinos, and the remainder leaks out more gradually than in a GRB. Consequently, the luminosity of a supernova at any given moment is a tiny fraction of that of a GRB. Even quasars, which are famously brilliant, give off only about 10^{40} watts.

If the burst beamed its energy in particular directions rather than in all directions, however, the luminosity estimate would be lower. Evidence for beaming comes from the way the afterglow of GRB990123, among others, dimmed over time. Two days into the burst, the rate of dimming increased suddenly, which would happen naturally if the observed radiation came from a narrow jet of material moving at close to the speed of light. Because of a relativistic effect, the observer sees more and more of the jet as it slows down. At some point, there is no more to be seen, and the apparent brightness begins to fall off more rapidly [see *illustration on next page*]. For GRB990123 and several other bursts, the inferred jet-opening angle is a few degrees. Only if the jet is aimed along our line of sight do we see the burst. This beaming effect reduces the overall energy emitted by the burst ap-

proximately in proportion to the square of the jet angle. For example, if the jet subtends 10 degrees, it covers about one 500th of the sky, so the energy requirement goes down by a factor of 500; moreover, for every GRB that is observed, another 499 GRBs go unseen. Even after taking beaming into account, however, the luminosity of GRB990123 was still an impressive 10^{43} watts.

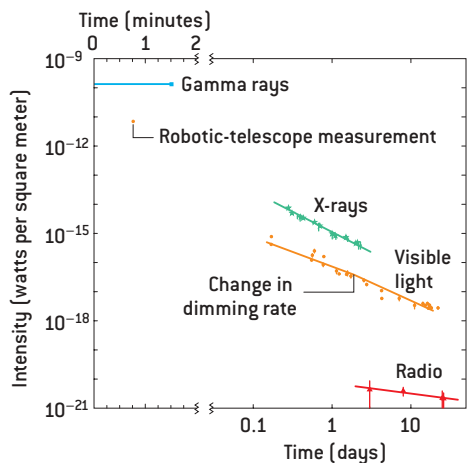
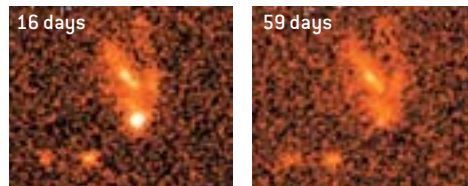
GRB-SUPERNOVA CONNECTION

ONE OF THE MOST interesting discoveries has been the connection between GRBs and supernovae. When telescopes went to look at GRB980425, they also found a supernova, designated SN1998bw, that had exploded at about the same time as the burst. The probability of a chance coincidence was one in 10,000 [see “Bright Lights, Big Mystery,” by George Musser; News and Analysis, SCIENTIFIC AMERICAN, August 1998].

A link between GRBs and supernovae has also been suggested by the detection of iron in the x-ray spectra of several bursts. Iron atoms are known to be synthesized and dumped into interstellar space by supernova explosions. If these atoms are stripped of their electrons and

FADING AWAY

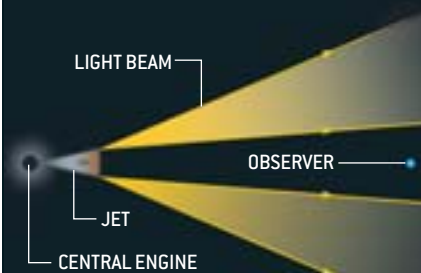
BRIGHTEST GAMMA-RAY BURST yet recorded went off on January 23, 1999. Telescopes tracked its brightness in gamma rays (*blue in graph*), x-rays (*green*), visible light (*orange*) and radio waves (*red*). At one point, the rate of dimming changed abruptly—a telltale sign that the radiation was coming from narrow jets of high-speed material. About two weeks into the burst, after the visible light had dimmed by a factor of four million, the Hubble Space Telescope took a picture and found a severely distorted galaxy. Such galaxies typically have high rates of star formation. If bursts are the explosions of young stars, they should occur in just such a place.



BEAM LINES

RELATIVITY PLAYS TRICKS on observers' view of jets from gamma-ray bursts.

1 Moving at close to the speed of light, the jet emits light in narrow beams. Some beams bypass the observer.



2 As the jet slows, the beams widen, so fewer of them bypass the observer. More of the jet comes into view.



3 Eventually beams from the edges reach the observer. The entire jet is now visible. Data reveal this transition.



later hook up with them again, they give off light at distinctive wavelengths, referred to as emission lines. Early, marginal detections of such lines by BeppoSAX and the Japanese x-ray satellite ASCA in 1997 have been followed by more solid measurements. Notably, NASA's Chandra X-ray Observatory detected iron lines in GRB991216, which yielded a direct distance measurement of the GRB. The figure agreed with the estimated distance of the burst's host galaxy.

Additional observations further support the connection between GRBs and supernovae. An iron-absorption feature appeared in the x-ray spectrum of GRB-990705. In the shell of gas around another burst, GRB011211, the European Space Agency's X-ray Multi-Mirror satellite found evidence of emission lines from silicon, sulfur, argon and other elements commonly released by supernovae.

Although researchers still debate the matter, a growing school of thought holds that the same object can produce, in some cases, both a burst and a supernova. Because GRBs are much rarer than supernovae—every day a couple of GRBs go off somewhere in the universe, as opposed to hundreds of thousands of supernovae—not every supernova can be associated with a burst. But some might be. One version of this idea is that supernova explosions occasionally squirt out jets of material, leading to a GRB. In most of these cases, astronomers would see either a supernova or a GRB, but not both. If the jets were pointed toward Earth, light from the burst would swamp light from the supernova; if the jets were aimed in another direction, only the supernova would be visible. In some cases, however, the jet would be pointed just slightly away from our line of sight, let-

ting observers see both. This slight misalignment would explain GRB980425.

Whereas this hypothesis supposes that most or all GRBs might be related to supernovae, a slightly different scenario attributes only a subset of GRBs to supernovae. Roughly 90 of the bursts seen by BATSE form a distinct class of their own, defined by ultralow luminosities and long spectral lags, meaning that the high- and low-energy gamma-ray pulses arrive several seconds apart. No one knows why the pulses are out of sync. But whatever the reason, these strange GRBs occur at the same rate as a certain type of supernova, called Type Ib/c, which occurs when the core of a massive star implodes.

GREAT BALLS OF FIRE

EVEN LEAVING ASIDE the question of how the energy in GRBs might be generated, their sheer brilliance poses a paradox. Rapid brightness variations suggest that the emission originates in a small region: a luminosity of 10^{19} suns comes from a volume the size of one sun. With so much radiation emanating from such a compact space, the photons must be so densely packed that they should interact and prevent one another from escaping. The situation is like a crowd of people who are running for the exit in such a panic that that nobody can get out. But if the gamma rays are unable to escape, how can we be seeing GRBs?

The resolution of this conundrum, developed over the past several years, is that the gammas are not emitted immediately. Instead the initial energy release of the explosion is stored in the kinetic energy of a shell of particles—a fireball—moving at close to the speed of light. The particles include photons as well as electrons and their antimatter counterpart, positrons. This fireball expands to a diameter of 10 billion to 100 billion kilometers, by which point the photon density has dropped enough for the gamma rays to escape unhindered. The fireball then converts some of its kinetic energy into electromagnetic radiation, yielding a GRB.

The initial gamma-ray emission is most likely the result of internal shock waves within the expanding fireball. Those shocks are set up when faster blobs

THE AUTHORS

NEIL GEHRELS, LUIGI PIRO and PETER J. T. LEONARD bring both observation and theory to the study of gamma-ray bursts. Gehrels and Piro are primarily observers—the lead scientists, respectively, of the Compton Gamma Ray Observatory and the BeppoSAX satellite. Leonard is a theorist, and like most theorists, he used to think it unlikely that the bursts were bright enough to be seen across the vastness of intergalactic space. “I have to admit that the GRBs really had me fooled,” he says. Gehrels is head of the Gamma Ray, Cosmic Ray and Gravitational Wave Astrophysics Branch of the Laboratory for High Energy Astrophysics at the NASA Goddard Space Flight Center. Piro is a member of the Institute of Space Astrophysics and Cosmic Physics of the CNR in Rome. Leonard works for Science Systems and Applications, Inc., in support of missions at Goddard.

in the expanding material overtake slower blobs. Because the fireball is expanding so close to the speed of light, the timescale witnessed by an external observer is vastly compressed, according to the principles of relativity. So the observer sees a burst of gamma rays that lasts only a few seconds, even if it took a day to produce. The fireball continues to expand, and eventually it encounters and sweeps up surrounding gas. Another shock wave forms, this time at the boundary between the fireball and the external medium, and persists as the fireball slows down. This external shock nicely accounts for the GRB afterglow emission and the gradual degradation of this emission from gamma rays to x-rays to visible light and, finally, to radio waves.

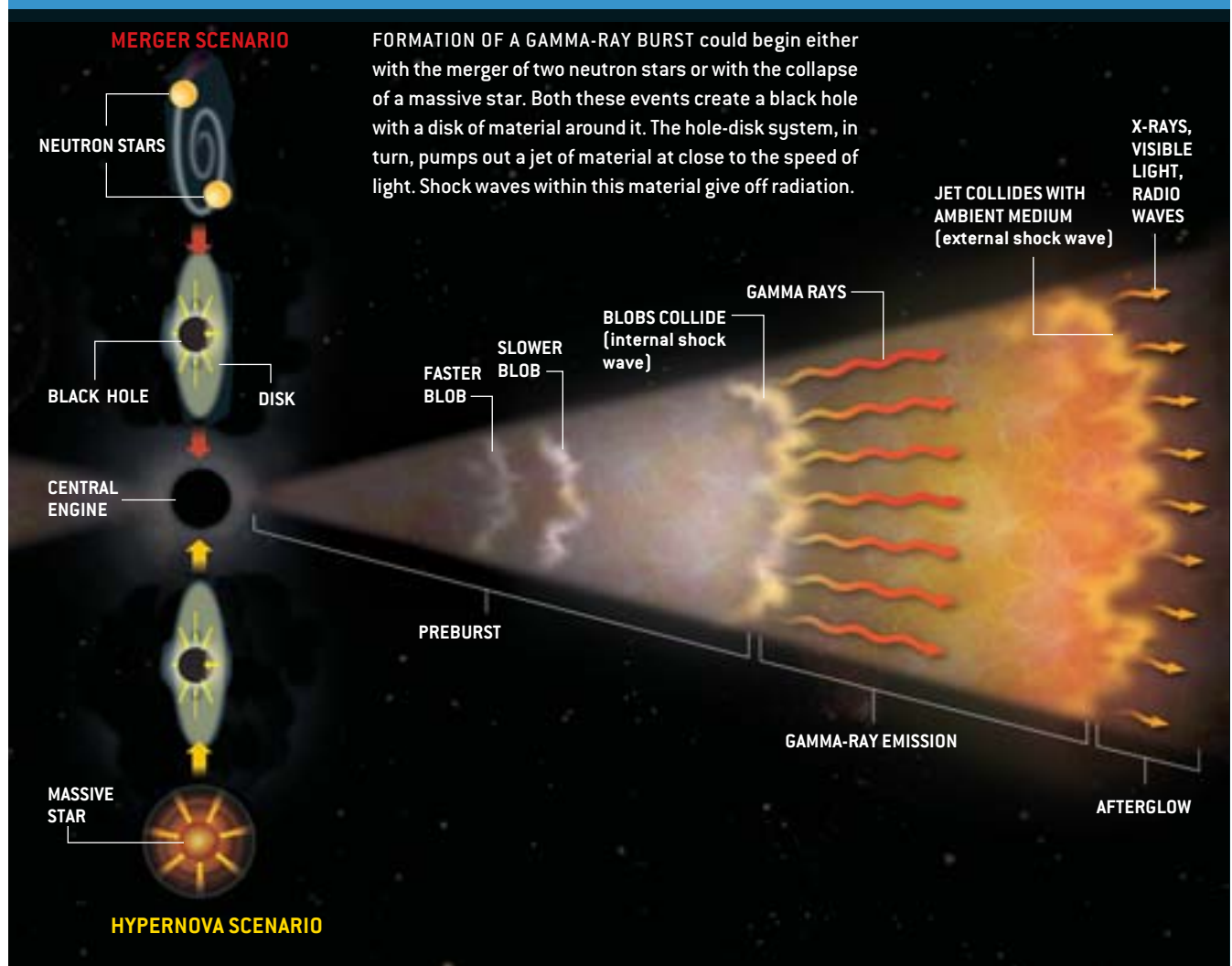
Although the fireball can transform the explosive energy into the observed radiation, what generates the energy to begin with? That is a separate problem, and astronomers have yet to reach a consensus. One family of models, referred to as hypernovae or collapsars, involves stars born with masses greater than about 20 to 30 times that of our sun. Simulations show that the central core of such a star eventually collapses to form a rapidly rotating black hole encircled by a disk of leftover material.

A second family of models invokes binary systems that consist of two compact objects, such as a pair of neutron stars (which are ultradense stellar corpses) or a neutron star paired with a black hole. The two objects spiral toward each other and

merge into one. Just as in the hypernova scenario, the result is the formation of a single black hole surrounded by a disk.

Many celestial phenomena involve a hole-disk combination. What distinguishes this particular type of system is the sheer mass of the disk (which allows for a gargantuan release of energy) and the lack of a companion star to resupply the disk (which means that the energy release is a one-shot event). The black hole and disk have two large reservoirs of energy: the gravitational energy of the disk and the rotational energy of the hole. Exactly how these would be converted into gamma radiation is not fully understood. It is possible that a magnetic field, 10^{15} times more intense than Earth's magnetic field, builds up during the formation of the

BURSTING OUT



disk. In so doing, it heats the disk to such high temperatures that it unleashes a fireball of gamma rays and plasma. The fireball is funneled into a pair of narrow jets that flow out along the rotational axis.

Because the GRB emission is equally well explained by both hypernovae and compact-object mergers, some other qualities of the bursts are needed to decide between these two scenarios. The association of GRBs with supernovae, for example, is a point in favor of hypernovae, which, after all, are essentially large supernovae. Furthermore, GRBs are usually found just where hypernovae would be expected to occur—namely, in areas of recent star formation within galaxies. A massive star blows up fairly soon (a few million years) after it is born, so its deathbed is close to its birthplace. In contrast, compact-star coalescence takes much longer (billions of years), and in the meantime the objects will drift all over the

galaxy. If compact objects were the culprit, GRBs should not occur preferentially in star-forming regions.

Although hypernovae probably explain most GRBs, compact-star coalescence could still have a place in the big picture. This mechanism may account for the poorly understood short-duration GRBs. Moreover, additional models for GRBs are still in the running. One scenario produces the fireball via the extraction of energy from an electrically charged black hole. This model suggests that both the immediate and the afterglow emissions are consequences of the fireball sweeping up the external medium. Astronomers have come a long way in understanding gamma-ray bursts, but they still do not know precisely what causes these explosions, and they know little about the rich variety and subclasses of bursts.

All these recent findings have shown that the field has the potential for an-

swering some of the most fundamental questions in astronomy: How do stars end their lives? How and where are black holes formed? What is the nature of jet outflows from collapsed objects?

BLASTS FROM THE PAST

ONE OUTSTANDING question concerns the dark, or “ghost,” GRBs. Of the roughly 30 GRBs that have been localized and studied at wavelengths other than gamma rays, about 90 percent have been seen in x-rays. In contrast, only about 50 percent have been seen in visible light. Why do some bursts fail to shine in visible light?

One explanation is that these GRBs lie in regions of star formation, which tend to be filled with dust. Dust would block visible light but not x-rays. Another intriguing possibility is that the ghosts are GRBs that happen to be very far away. The relevant wavelengths of light produced by the burst would be absorbed by intergalactic gas. To test this hypothesis, measurement of the distance via x-ray spectra will be crucial. A third possibility is that ghosts are optically faint by nature. Currently the evidence favors the dust explanation. High-sensitivity optical and radio investigations have identified the probable host galaxies of two dark GRBs, and each lies at a fairly moderate distance.

Another mystery concerns a class of events known as the x-ray-rich GRBs, or simply the x-ray flashes. Discovered by BeppoSAX and later confirmed by re-analysis of BATSE data, these bursts are now known to represent 20 to 30 percent of GRBs. They give off more x-radiation than gamma radiation; indeed, extreme cases exhibit no detectable gamma radiation at all.

One explanation is that the fireball is loaded with a relatively large amount of baryonic matter such as protons, making for a “dirty fireball.” These particles increase the inertia of the fireball, so that it moves more slowly and is less able to boost photons into the gamma-ray range. Alternatively, the x-ray flashes might come from very distant galaxies—even more distant than the galaxies proposed to explain the ghost GRBs. Cosmic expansion would then shift the gamma rays into the x-ray range, and intergalactic gas

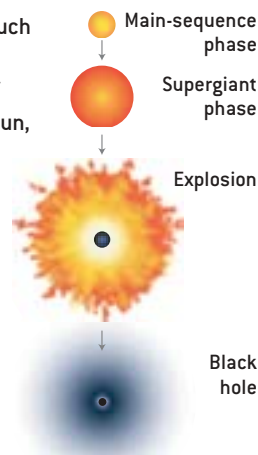
The Destinies of Massive Stars

STARS SPEND MOST OF THEIR LIVES in the relatively unexciting main-sequence evolutionary phase, during which they casually convert hydrogen into helium in their cores via nuclear fusion. Our sun is in this phase. According to basic stellar theory, stars more massive than the sun shine more brightly and burn their fuel more quickly. A star 20 times as massive as the sun can keep going for only a thousandth as long.

As the hydrogen in the core of a star runs out, the core contracts, heats up and starts to fuse heavier elements, such as helium, oxygen and carbon. The star thus evolves into a giant and then, if sufficiently massive, a supergiant star. If the initial mass of the star is at least eight times that of the sun, the star successively fuses heavier and heavier elements in its interior until it produces iron. Iron fusion does not release energy—on the contrary, it uses up energy. So the star suddenly finds itself without any useful fuel.

The result is a sudden and catastrophic collapse. The core is thought to turn into a neutron star, a stellar corpse that packs at least 40 percent more mass than the sun into a ball with a radius of only 10 kilometers. The remainder of the star is violently ejected into space in a powerful supernova explosion.

There is a limit to how massive a neutron star can be—namely, two to three times as massive as the sun. If it is any heavier, theory predicts it will collapse into a black hole. It can be pushed over the line if enough matter falls onto it. It is also possible that a black hole can be formed directly during the collapse. Stars born with masses exceeding roughly 20 solar masses may be destined to become black holes. The creation of these holes provides a natural explanation for gamma-ray bursts.



—N.G., L.P. and P.J.T.L.

Classes of Gamma-Ray Bursts

| BURST CLASS (SUBCLASS) | PERCENTAGE OF ALL BURSTS | TYPICAL DURATION OF INITIAL EMISSION (SECONDS) | INITIAL GAMMA-RAY EMISSION | AFTERGLOW X-RAY EMISSION | AFTERGLOW VISIBLE EMISSION | HYPOTHETICAL CENTRAL ENGINE | EXPLANATION FOR PECULIAR PROPERTIES |
|------------------------------------|--------------------------|--|----------------------------|--------------------------|----------------------------|-------------------------------------|--|
| Long (normal) | 25 | 20 | ✓ | ✓ | ✓ | Energetic explosion of massive star | Not applicable |
| Long (ghosts or dark) | 30 | 20 | ✓ | ✓ | ✗ | Energetic explosion of massive star | Extremely distant, obscured by dust, or intrinsically faint |
| Long (x-ray-rich or x-ray flashes) | 25 | 30 | ✗ | ✓ | ✗ | Energetic explosion of massive star | Extremely distant or weighed down by extra particles |
| Short | 20 | 0.3 | ✓ | ? | ? | Merger of pair of compact objects | Does not occur in a star-forming region, so ambient gas is less dense and external shocks are weaker |

would block any visible afterglow. In fact, none of these x-ray flashes has a detectable visible-light counterpart, a finding that is consistent with this scenario. If either x-ray flashes or ghost GRBs are located in extremely distant galaxies, they could illuminate an era in cosmic history that is otherwise almost invisible.

The next step for GRB astronomy is to flesh out the data on burst, afterglow and host-galaxy characteristics. Observers need to measure many hundreds of bursts of all varieties: long and short, bright and faint, bursts that are mostly gamma rays, bursts that are mostly x-rays, bursts with visible-light afterglows and those without. Currently astronomers are obtaining burst positions from the second High Energy Transient Explorer satellite, launched in October 2000, and the Interplanetary Network, a series of small gamma-ray detectors piggybacking on planetary spacecraft. The Swift mission, scheduled for launch next fall, will offer multiwavelength observations of hundreds of GRBs and their afterglows. On discovering a GRB, the gamma-ray instrument will trigger automatic onboard x-ray and optical observations. A rapid response will determine whether the GRB has an x-ray or visible afterglow. The mission will be sensitive to short-duration bursts, which have barely been studied so far.

Another goal is to probe extreme gamma-ray energies. GRB940217, for example, emitted high-energy gamma rays for more than an hour after the burst, as observed by the Energetic Gamma Ray Experiment Telescope instrument on the Compton Gamma Ray Observatory. Astronomers do not understand how such extensive and energetic afterglows can be produced. The Italian Space Agency's AGILE satellite, scheduled for launch in 2004, will observe GRBs at these high energies. The supersensitive Gamma-Ray Large Area Space Telescope mission, expected to launch in 2006, will also be key for studying this puzzling phenomenon.

Other missions, though not designed solely for GRB discovery, will also contribute. The International Gamma-Ray Astrophysics Laboratory, launched on

October 17, is expected to detect 10 to 20 GRBs a year. The Energetic X-ray Imaging Survey Telescope, planned for launch a decade from now, will have a sensitive gamma-ray instrument capable of detecting thousands of GRBs.

The field has just experienced a series of breakthrough years, with the discovery that GRBs are immense explosions occurring throughout the universe. Bursts provide us with an exciting opportunity to study new regimes of physics and to learn what the universe was like at the earliest epochs of star formation. Space- and ground-based observations over the coming years should allow us to uncover the detailed nature of these most remarkable beasts. Astronomers can no longer talk of bursts as utter mysteries, but that does not mean the puzzle is completely solved. SA

MORE TO EXPLORE

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