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Gamma-Ray Bursts, Black Holes and the Universe

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Long, Long Ago and Far, Far Away

1. Gamma-Ray Bursts

1.1. Yet Another Cosmic Mystery

There was a revolution in astronomy in the first few months of 1997. A major breakthrough occurred in one of the outstanding mysteries of modern astrophysics, the cosmic *gamma-ray bursts*. This story began in the 1960s. The United States launched a series of satellites that orbited the Earth at great distance, halfway to the Moon. They were called the *Vela* series, and they were designed to detect gamma rays and other high-energy photons and particles. If it strikes you that there must be something special about them to be so far from Earth, you are on the right track. They were not designed for astronomy, but primarily to detect terrestrial nuclear bomb tests. They were also intended to study the background, other natural sources of high-energy photons and particles in the solar wind and the Earth's magnetosphere, to aid in the separation of bomb signals from natural signals.

Stirling Colgate was on the team in Geneva in1963 working on the treaty to ban space, atmospheric, and underwater nuclear tests. He had done some calculations that suggested that when a supernova shock wave broke through the surface of the star there could be a pulse of gamma rays (see Section 2.4 for an update of this topic). He was afraid that such an event would be misunderstood as a nuclear bomb and might trigger a serious miscalculation by one side or the other. He hassled both sides, the United States and the Soviets, concerning the need to understand potential astronomical sources of confusion, especially supernovae, lest they lead to disaster. In terms of giving credit, Colgate revealed the true father of modern supernova and gamma-ray burst research: “Scratchy” Serapkin. Anatoly Serapkin was the head of the Soviet delegation to the Geneva talks aimed at the Limited Test Ban Treaty. When Colgate said supernovae might be confused with a test, Scratchy, not a scientist himself, fixed him with a steely glare and inquired, “Who knows how supernovae work?” Colgate realized what thin ground he, and the U.S. delegation, were on. He returned to Livermore and made the case to Edward Teller that understanding supernovae must become a primary goal of the Lawrence Livermore Laboratory. The rest is history, much of it recounted in Chapters 6 and 7.

The *Vela* satellites were motivated, at least in part, by these concerns. Colgate found the Russians intractable. They would not do their own astrophysical background checks and feared satellites launched by the United States would be used for spying. The agreement to put the *Vela* satellites in high orbit was a response to the Russian demand for a guarantee that they not be used for spying. Both sides did launch spy satellites, of course, but this did not apply to the *Vela* series, the results of which were unclassified.

Perhaps the *Vela* series saw bombs, but they certainly detected outbursts of an extraterrestrial nature. One of the *Vela* series was instrumented to see X-rays and discovered the first X-ray burst (Chapter 8, Section 7). With the first extraterrestrial detections of gamma rays in 1967 (the *Vela 4* series), the scientists at Los Alamos could not convincingly rule out the Sun as the source. They had to wait until the launch of the next series (*Vela 5*) in 1969 before they were able to conclude rigorously that the gamma-ray signals were from neither the Earth nor the Sun but from elsewhere in outer space. The discovery was finally announced by Ray Klebesadel, Ian Strong, and Roy Olson in a paper in the *Astrophysical Journal* in 1973. This paper created a new scientific industry.

The bursts of gamma rays from beyond the Earth were seen at irregular intervals. These bursts lasted for 10–30 seconds and showed variations on times as short as a 0.001 second. Subsequent investigations showed that the gamma-ray bursts were primarily a gamma-ray phenomenon, with relatively little energy in the X-ray band, unlike other sources of gamma rays that emit abundantly at lower energies as well. That the dominant emission mode is gamma rays means that a high energy is involved. Gamma-ray bursts probably require high gravity and motion at nearly the speed of light.

The quest for an explanation of gamma-ray bursts was long handicapped by a lack of direct knowledge of the distance to the bursts. A debate raged as to whether they are in the Galaxy or at the farthest reaches of the Universe. This debate was brought into sharp focus by the immensely successful Burst And Transient Source Experiment (*BATSE*) on the *Compton Gamma-Ray Observatory*. The *Compton Gamma-Ray Observatory*, named for Arthur Holly Compton (Chapter 10), was launched in 1991 as one of the series of Great Observatories planned by NASA. The *Hubble Observatory* was the first. Two others, the *Advanced X-ray Astronomy Facility (AXAF)* and the *Space Infrared Telescope Facility (SIRTF*), were downsized, descoped, and delayed for over a decade, but *AXAF* was finally launched as the successful *Chandra Observatory* in July 1999, and *SIRTF* was launched in August 2003 as the *Spitzer Space Telescope*. In the meantime, the *Compton Gamma-Ray Observatory*, with *BATSE* aboard, was de-orbited in June, 2000. The dream of having all four Great Observatories in orbit at once was not realized, but the record is still fantastic, with, at this writing, *Hubble* in maturity, *Chandra* in ripe middle age, and *Spitzer* the active new kid on the block.

BATSE recorded 2704 new gamma-ray bursts in its active life, corresponding to about one per day. The surprising result was that the sources are, to great accuracy, distributed uniformly on the sky. There is no statistical evidence for any tendency to lie toward the plane of the disk of our Galaxy or toward the galactic center. This contradicted any picture in which the sources were distributed throughout the Galaxy and viewed from the offset position of the Earth, 25,000 light years from the galactic center. This result fueled increasing conviction that the sources of the gamma-ray bursts were in galaxies at cosmological distances because the distant galaxies are naturally distributed uniformly on the sky, on average. In addition, fainter sources are more abundant. The precise number of faint sources shows a pattern that is close to what one would expect if the bursts constituted a gamma-ray standard candle viewed in ever-larger volumes of space in an expanding Universe. There might, however, be other explanations for this pattern, and there is no particular reason to think that gamma-ray bursts are a standard gamma-ray candle.

The problem is that if the gamma-ray bursts are at cosmological distances, the intrinsic source of energy must be huge, comparable to or exceeding that of a supernova, but radiated essentially entirely in gamma rays. Everything about the cosmic gamma-ray bursts strains credibility, yet there they are.

One of the clearly defined problems in the study of gamma-ray bursts was the complete lack of counterpart events at other wavelengths, especially optical wavelengths. Without optical counterparts, the full weight of astronomical lore, much of it derived from optical astronomy, could not be brought to bear on the issue. The problem was that the gamma-ray detectors could not provide sufficiently good locations. It is a difficult technical feat to bring gamma rays to focus. The gamma-ray sky has typically been "fuzzy," a situation somewhat analogous to nearsighted people looking around with their glasses off. A given gamma-ray burst could be said to be "over there," but "there" could not be precisely defined. The uncertainties in position were typically several to tens of degrees in radius (the full Moon subtends about 0.5 degree in angular diameter). In an area of the sky of that size, there can be thousands of stars. Finding the point of light that corresponds to a given 10-second-long gamma-ray burst was like seeking the proverbial needle in a haystack, a needle that was likely to vanish if you did not find it in less than a minute.

The nature of these events puzzled astrophysicists for nearly 30 years. Without the fetters of any relation to classical astronomy, theorists had a field day trying to explain the observations. The requirements for a theory in these circumstances are that it account for the observations and be self-consistent. Plausibility was not necessarily a constraint because gamma-ray bursts represented a new and unprecedented phenomenon. At a meeting shortly after their discovery, Mal Ruderman of Columbia University, who was giving the review talk on gamma-ray bursts, announced that it was easier to give a list of the people who had not presented a theory of gamma-ray bursts than it was to give a list of those who had. He showed a slide consisting of one name, Princeton's Jerry Ostriker who, for whatever reason, had not jumped on the gamma-ray burst bandwagon.

Theories ranged from black hole collapse to "relativistic bb's." The latter were supposed to be little grains of dust accelerated to near the speed of light and then arriving at the Solar System to crash energetically into the solar wind. Remember all the billion pulsars that have died in the Galaxy? One of the first theories, and one that generated more than a few chuckles, postulated that gamma-ray bursts were generated by comets falling onto those neutron stars. One of the little-known but supportive ideas of this hypothesis is that clouds of comets may very well spread nearly from one star to another. Space may be filled with comets, and the chance that one of them would occasionally fall onto one of those billions of neutron stars is not so low.

The argument that swayed some people into taking this comet idea more seriously is the problem of generating gamma rays at all with a neutron star. The problem is related to the Eddington limit (Chapter 2). If energy is released on the surface of a neutron star, the material expands and cools in response to the radiation pressure. Under normal circumstances, such matter can get hot enough to emit X-rays, as we have seen in Chapter 8, but not hot enough to emit the more energetic gamma rays. The importance of the impact picture is that the material arrives in a lump and is compressed much more than would be either a dribble of gas or material just sitting on the surface. The effect might be enhanced if the infalling matter were a rock, so asteroids as well as comets have been considered. After a hiatus of a number of years, a similar idea was still around in 1998, although it sank under the weight of recent results.

There is a benefit to allowing the imagination of the theorists to run the bounds of the known data. What was really needed were more data so that theory and observation could march hand in hand in some fruitful direction.

1.2. The Revolution

All this changed with the launch of a Dutch-Italian X-ray satellite, *BeppoSAX* on April 30, 1996. This wonderful name derives from the nickname of a pioneering Italian physicist and X-ray astronomer, Giuseppe Occhialini, known as Beppo to friends and colleagues, with the appendage for X-ray satellite in Italian, *Satellite per Astronomia a Raggi X. BeppoSAX* was capable of looking everywhere on the sky for the weaker X-ray signal that characterizes gamma-ray bursts and to give a first coarse location, more accurate than *BATSE* provided. The key innovation for *BeppoSAX* was a second instrument that could be brought to focus by quickly slewing the satellite in an attempt to rapidly find the X-ray flare from the gamma-ray burst and to provide a much more accurate location, with an uncertainty of a few minutes of arc, an area on the sky several times smaller than *BATSE* provided. At that point, ground-based optical telescopes could be brought to bear to search the much smaller location to see if there were any optical component. All this was a bit of a gamble. If the whole gamma-ray burst phenomenon in lower-energy X-rays and in the optical faded in the tens of seconds that characterized the gamma-ray bursts themselves, then there would be no time to slew the satellite, a process that would take at least hours, never mind time to obtain optical images, a process that might take a day (or night) even in the best of circumstances.

Another chapter of this story is worth telling if only to recognize the great effort and ingenuity that goes into the scientific enterprise that sometimes fails to pay off. At a meeting on gamma-ray bursts in Santa Cruz in the 1981, the attendees recognized that studies of gamma-ray bursts were stymied by the lack of observations at other wavelengths. A project was born to design a satellite that would contain a gamma-ray detector, but also ultraviolet and optical detectors to look in the same direction and hence to get simultaneous information on the burst at other wavelengths. The project was named *HETE* for *High-Energy Transient Explorer* and the arduous process of design began. It won NASA competitions to build and launch and suffered the inevitable delays. *HETE* was finally scheduled to launch on November 4, 1996, a date that would have put it in competition with *BeppoSAX*. The Pegasus rocket carried *HETE* and an Argentine satellite to orbit, but a battery failed in the third stage. The shroud that held them could not be opened, and without its solar panels, *HETE* died in the darkened enclosure. That opened the way for *BeppoSAX*. To their credit, the *HETE* team regrouped, took the plans and spare parts, and built a new satellite. *HETE 2* was launched on October 9, 2000 and has been a valuable tool for the study of gamma-ray bursts, as will be outlined below. With the satellites still in its grip, the third stage of the Pegasus that carried *HETE I* aloft burned up in the atmosphere on April 6, 2002 over the Indian Ocean,

BeppoSAX scored its coup on February 28, 1997, when it localized a burst sufficiently well that an optical follow-up was feasible. The result was the discovery of the first optical counterpart by a team led by Dutch astronomer Jan Van Paradijs. Van Paradijs saw the great flowering of gamma-ray burst research that followed from this identification, but was tragically struck down by cancer only two years later.

The fashion has been to label gamma-ray bursts by the year and day that they were discovered. Occasionally, two or more events have been discovered on the same day to mess up this scheme; then they get appendages of a, b, c, etc. With this convention, the breakthrough gamma-ray burst was thus named GRB 970228.

Two months later, in early May, *BeppoSAX* found another event, GRB 970508, enabling another optical identification. In this case, absorption lines of matter in front of this source proved that the source was at a cosmological distance, of order 1 billion light years or greater. In December of 1997, yet another optical counterpart was discovered associated with GRB 971214. After the gamma-ray burst faded, a faint galaxy was revealed. The red shift of this galaxy was immense, with the wavelength of the detected light shifted by more than a factor of 3 from its natural wavelength. This galaxy was estimated to be 12 billion light years away. If GRB 971214 had radiated equally into all directions and hence followed the basic inverse-square law for apparent brightness (Section 1.2), then estimating the distance from the red shift (and adopting specific values of the cosmological parameters) implied that the energy of this source was fantastically large. More energy would be required than the entire collapse and neutrino energy of a supernova and more than even most exotic theories of colliding neutron stars and black holes could support.

Even GRB 971214 is not the record. That belongs to the first burst localized by *BeppoSAX* in 1999, GRB 990123. This burst brought in yet another interesting chapter in the saga. Many people realized that if an optical counterpart were ever to be seen, then an especially rapid response was needed. A special email notice system run by Scott Barthelmy and his colleagues at the NASA Goddard Space Flight Center in Maryland was set up. Even more extreme, some people began to wear beepers that were triggered electronically by a signal from a satellite, *BATSE* or *BeppoSAX*, so that they got buzzed the instant (allowing for the finite travel time of light and relay switches) a gamma-ray burst was detected. One of the things that this rapid response allowed was communication with automatically controlled robotic telescopes that would very quickly swivel to look for an optical counterpart, perhaps in the time frame of the original gamma-ray burst. This was the mission of *ROTSE*, the *Robotic Optical Transient Search Experiment*.

The first generation, *ROTSE I,* was a small telescope situated at the Los Alamos National Laboratory. It was designed and operated by Carl Akerlof and his associates at the University of Michigan, Los Alamos, and the Lawrence Livermore National Laboratory. *ROTSE I* was constructed to receive signals directly from the satellites that detect gamma-ray bursts and then to rapidly swivel and look at the location of a gamma-ray burst. *ROTSE I* was not very sensitive as telescopes go because it had only four wide-angle camera telephoto lenses, but it could see a fairly large portion of the sky at one time to look for variable sources. Another advantage is that it was quick! Quickness does not count if the weather does not cooperate or if the discovered gamma-ray burst is only visible from the southern hemisphere or if it is “up” in the north during daylight hours. This was the tale for the first number of *BeppoSAX* bursts. *ROTSE I* did have a clean shot at some bursts, but it did not see anything.

Finally, on January 23, 1999, everything came together, and *ROTSE I* scored its first detection of a gamma-ray burst. *ROTSE I* detected the immediate optical counterpart of GRB 990123, the emission of light that occurs simultaneously with the burst itself. The results were dramatic. *ROTSE I* saw a flash of light that rose in about 10 seconds to ninth magnitude and then faded over the next minute or so. This peak apparent brightness was only about a factor of 10 dimmer than can be seen with the naked eye! Associated work on this gamma-ray burst revealed it to be at yet another immense distance. This makes GRB 990123 the intrinsically brightest optical event ever recorded in scientific history. Ho hum, another record for gamma-ray bursts. Actually, there is nothing to be blasé about here. If radiated uniformly in all directions, the implied peak optical luminosity of GRB 990123 was equivalent to ten million supernovae or ten thousand very bright quasars. This optical burst did not last long, but its intensity was very impressive.

Most of the energy emitted by GRB 990123 was in the gamma-ray range. Here again, GRB 990123 set a record. The detected gamma-ray intensity was among the strongest ever seen at the Earth. At the distance observed, the total energy in gamma rays was ten times higher than the previous record-setters like GRB 971214. If this gamma-ray energy poured out equally in all directions, the energy involved was equivalent to the complete annihilation of 2 solar masses of matter! One runs out of exclamation points.

These optical counterparts of the cosmic gamma-ray bursts thus revolutionized the field and proved the power of focusing optical astronomy on this decades-old problem. They opened a new era in the study of gamma-ray bursts that provided not only rapid progress in understanding the bursts themselves, but also promise of their use to explore the nature of the Universe at great distances.

The emission witnessed in the X-rays by *BeppoSAX*, in the optical by ground-based telescopes, and in the radio by radio telescopes, was discovered to last much longer than the original gamma-ray burst. Rather than tens of seconds, the X-rays last for days, and the optical and radio can stay above limits of detectability for weeks or months. This delayed emission of energy has been termed the *afterglow* of the gamma-ray burst. The general interpretation is that the process that energizes the event, whatever that process is, sends a powerful explosion out into the interstellar gas surrounding the event. The explosion generates a strong shock wave that moves at very nearly the speed of light. The interaction of this shock wave with the interstellar gas can produce gamma rays, X-rays, optical emission, and radio emission in appropriate circumstances. The general process leading to this afterglow is called a *relativistic blast wave*. Models based on this process have been successful in accounting for many of the observations of the afterglow, including the spectrum of the radiation and the rate of decay that tends to drop off as one over the time since the original gamma-ray burst. If you wait twice as long, the glow is half as bright.

As remarked above, *HETE 2*, was launched in October of 2000. *BeppoSAX* continued to operate until April of 2002. *HETE 2* was not as effective as the most optimistic predictions for a variety of technical reasons, but it has provided data on key bursts that have driven progress in the field. The new kid on the block is the *Swift* satellite, launched on November 20, 2004. This satellite is just coming into full operation as this is being written. *Swift* is engineered to both discover gamma-ray bursts and to follow the optical afterglow with its own on-board telescope. There is also a global effort to respond to bursts with ground based instruments, from small robotic telescopes to the giant telescopes that dot the planet, the Hobby-Eberly telescope in Texas, the Keck Telescopes in Hawaii, the Gemini telescopes in Chile and Hawaii, the four Very Large Telescopes at the European Southern Observatory in Chile. There has been dramatic progress, but there is so much more to do.

SIDEBAR The ROTSE Story

[rfI am involved in one of the robotic telescope projects, and there is a story there. The *ROTSE* team at the University of Michigan led by Carl Akerlof designed a second generation robotic telescope with a larger aperture, but smaller field of view than *ROTSE I*. The idea was that one could afford a somewhat smaller field of view with more accurate first-cut satellite positions as the expense of being able to peer to fainter limits. ROTSE II was a bust for technical reasons. I am not sure what the problems were; Carl does not like to talk about it. In any case, the team pushed on to a third generation of telescopes, *ROTSE III*. These are small telescopes, with mirrors only about eighteen inches in diameter, but they can observe nearly two square degrees at a time and they are snake-fast. From receipt of an electronic command, a ROTSE III telescope can be making fully robotic observations a mere six seconds later! This is the fastest response time of any similar instruments. One key goal is to search for the optical flash that is simultaneous with the gamma-ray burst itself, as was done by *ROTSE I* for GRB 990123. Even the *Swift* satellite itself will not routinely do that. *Swift* requires about a minute to train its optical telescope on any burst it discovers. The telescopes are housed in small enclosures reminiscent of, but somewhat larger than a porto-potty. They have tops that flip open automatically and are fully instrumented with weather stations to monitor conditions.

The chain of events involving me started at a meeting of the American Astronomical Society in June of 2001. Carl Akerlof gave a talk in which he outlined the success of *ROTSE I* and his proposed plan for four *ROTSE III* telescopes spaced around the world to provide maximal coverage. He mentioned that they were still exploring sites for the telescopes. As pure blind luck would have it, Carl sat down next to me after his talk. We had never met. I introduced myself and, with my typical, fools-rush-in naivité, asked whether he might want to put one of the telescopes at McDonald Observatory. Carl was polite, but basically said “I don’t think so,” and excused himself to rush off to the airport. I put the incident out of my mind.

I got a phone call from Carl about two months later asking whether I might further consider the proposition of putting one of the *ROTSE III* instruments in Texas. Still having little idea what I was getting into, or exactly whose resources I was committing, I said “sure.” *ROTSE I* had been based at Los Alamos Laboratory, where gamma-ray bursts were discovered and where there was a long-standing interest and complementary projects for fast response telescopes. The presumption had been that one of the *ROTSE III* instruments would also go there;Texas was too close to provide the global geographical distribution that was desired. As it transpired, the lab administration gave indications of rather tepid support for *ROTSE*, among other things proposing to move the instruments from the lab grounds proper to a site 30 miles away in the mountains where routine access and maintenance would be cumbersome. In addition, it was always difficult, and becoming moreso, to get foreign associates onto the lab grounds, including that remote site. A Russian postdoctoral fellow was having such access problems and *ROTSE III* was designed to be an integrated foreign collaboration. That tipped the balance of a difficult decision away from Los Alamos and to Texas. Off we went.

The first *ROTSE III* instrument, christened *ROTSE IIIa*, was installed in Australia. Texas got the second, *ROTSE IIIb*. Figure XXX shows ROTSE IIIb in the foreground of the Hobby-Eberly Telescope. The third, *ROTSE IIIc,* was installed in Namibia where German scientists already had a radio telescope site and another type of telescope to monitor the air showers formed by gamma-rays. The fourth, *ROTSE IIId,* has been set up in Turkey. ROTSE IIIa and b have already done some interesting work with *HETE 2* bursts and are poised to be useful tools in the *Swift* era.

History played out in the background of these developments. The 9/11 attack came shortly after we decided to move the telescope to Texas. One of the minor, but significant, results was an even higher attention to security at Los Alamos. In addition, *ROTSE III* was installed at McDonald Observatory in February of 2003. A bunch of us were sitting in the Astronomer's Lodge at the observatory on the morning of February 3rd, having breakfast and planning the day's work when one of the young scientists looked up from his laptop and reported that CNN was saying that radio contact had been lost from the Space Shuttle Columbia. That brave crew had died over our heads only moments earlier without our knowing it.

On a lighter note, we dedicated *ROTSE IIIb* with a quintessentially Texas tradition. While ships are dedicated by smashing a bottle of champagne over the bow, I felt it more appropriate to the West Texas environment and culture to stomp a jalepeño pepper. We had done this once before with the dedication of a special purpose supernova search telescope. In this case, I again provided the jalepeños, and we have a nice little video of the team in fierce unison stomping the peppers into the grate work in front the enclosure door.

END SIDEBAR

1.3. The Shape of Things

One of the issues that had to be confronted in the study of gamma-ray bursts was the manner in which the energy is released into the surroundings. There are a number of tightly intertwined issues here. Theoretical models of relativistic blast waves and the afterglow demand that a shock wave moves out from the source at speeds very close to the speed of light. To do this, the flow of energy must carry along with it very few ordinary particles, protons, or more generally baryons (Chapter 1). Too many of these particles of ordinary matter would slow the shock wave down so that it could not propagate with the deduced speeds. That is one thing that must distinguish an ordinary supernova and a gamma-ray burst. Both events have roughly the same amount of energy, but supernovae put their energy into moving a lot of ordinary matter at high, but not relativistic speeds. Gamma-ray bursts must put as much or more energy into a very small amount of mass.

Given the expansion at nearly the speed of light, a number of issues arise that come from Einstein's special theory of relativity. When motion with respect to an observer is high, lengths are foreshortened, and times are constricted. A gamma-ray burst that takes a minute as observed at the Earth may have spread over a region the size of the Solar System at its origin. An event that takes several months to develop in the host galaxy of the gamma-ray burst may take only hours or days as observed at Earth. In particular, it may take many months for the relativistic shock wave to expand out from the source of energy, pile up mass in the interstellar medium, and slow to ordinary speeds. An observer on Earth would see all this playing out in a day or so. Turned around, when we see a gamma-ray burst afterglow fading over a few days, it might have taken months in a far galaxy.

Another interesting effect is that, if a source of radiation moves toward an observer at a high speed, the radiation is thrown in the direction of the observer. This "beaming" can make the radiation seem brighter than it would otherwise be. In addition, if the source of energy is moving toward the observer, there is a very large blue shift, a "boost" of the energy of each photon that is detected. This can again make the source look brighter.

Such issues arise in trying to determine how bright a given gamma-ray burst really is and how much energy it emits. Even if the energy from a gamma-ray burst is emitted equally in all directions, it will be beamed and boosted and look brighter for a shorter time to an observer standing still on the Earth compared to an observer at the same distance who moved with the velocity of the shock. Trying to figure out how bright a given gamma-ray burst "really" is in its own rest frame is a rather tricky business that requires an understanding of just how the boosting and beaming is working.

One can get a measure of the total energy emitted in the radiation independent of the beaming and boosting if the energy is emitted equally in all directions. The procedure is to add up all the energy received at Earth over the course of the burst event. That energy might have been emitted over a different time span in the frame of the explosion, but all the energy is all the energy, and it must all go somewhere eventually. If one assumes it goes off equally in all directions and corrects for the fact that things look dimmer by the inverse square of the distance (plus perhaps some corrections for cosmological warping), then the total energy in radiation of the explosion can be determined. For the first *BeppoSAX* events for which there was a measure of the red shift and hence the distance, the results were imposing, as mentioned earlier. For the event at the largest distance of the first few identified, GRB 971214 at12 billion light years appeared to have emitted an energy comparable to the entire flow of neutrinos from a supernova, a huge amount of energy, and for GRB 990123 the corresponding amount would have been 10 times the neutrino energy of a supernova. In the early, heady, days of the afterglow revolution this was labeled by some as a result that threatened to challenge physics at a fundamental level. Challenges to the core of physics do arise from some astronomical observations as we will see in Chapter 12, but in this case the problem while fascinating, had a more mundane yet far-reaching solution.

There is an important caveat to the method of measuring energy just outlined. If the flow of energy does not come out equally in all directions, if it is collimated in some way, if it flows out in a jet, then less total energy is required for a given observed burst, just in proportion to the amount of collimation, as shown in Figure 11.4. If the energy flows only into 10 percent of all available directions, then a given energy received on Earth requires only 10 percent as much total energy at the source. If the energy flows in a jet filling only 1 percent of the area around the source, then the energy at the source is only 1 percent of that deduced from the assumption that equal energy goes in all directions.

This collimation effect is not a fantasy. It is almost the rule rather than the exception. We see collimated flows from the Sun, protostars, planetary nebulae, binary black holes, and quasars. If the energy of a gamma-ray burst comes out in a collimated relativistic blast wave in only certain directions, then one must be careful in making estimates of luminosities and energies.

An example of this phenomenon is the "blazars." Blazars are a certain subclass of quasars that are especially bright and highly variable. The common interpretation is that in these objects we happen to be looking right down the nozzle of a jet of matter ejected at nearly the speed of light. By the accident of the Earth's position in the beam, we see an especially bright source of radiation because of the beaming and boosting associated with the rapid motion toward us. We also see especially rapid time variability of the radiation that is thought to be associated with the shrinkage of time due to the relativistic motion. No one suggests that this energy is flowing out equally in all directions, thus requiring unprecedented amounts of energy, even for quasars. Rather it is assumed that, if we happened to observe the same object from the side, it would resemble an “ordinary” quasar. Understanding whether, how, and how much gamma-ray bursts are collimated became one of the key tasks facing the field.

My colleague, Lifan Wang, and I were among the first to point that this “jetting” or “collimation” might both be expected for gamma-ray bursts and important for their analysis and that this property might link gamma-ray bursts to supernovae (next section). Our thinking was driven in part by our growing understanding from our polarization studies that core collapse supernovae were asymmetric and often even “jet-like.” As things developed, it turned out we were on the right track. The proof that gamma-ray bursts involved jets and were related to supernovae came from different quarters, but we take some satisfaction that we had the correct basic ideas.

Our idea was to see how far one could go with using only relatively ordinary supernovae to produce gamma-ray bursts. The argument was that all gravitational collapse events produce strong magnetic jets that punch out through the axes of the surrounding carbon/oxygen core. In ordinary Type II supernovae, the outer hydrogen layers would stop these jets. In Type Ic or Type Ib, the jet could escape into interstellar space making the gamma-ray burst. ***This is shown schematically in Figure 11.5. Keep? Move to SN chapter?***

In this picture, there are two components to the gamma-ray emission, one that radiates more or less equally in all directions with the energy about one thousand times less than a standard supernova expansion energy, and one component that is highly collimated in a relativistic jet containing perhaps 10 percent of the total supernova energy. The lower energy component could be seen if the explosion occurred relatively nearby, 100 million light years or less, but would not be detectable with current instruments if the same event were at truly cosmological distances. The other gamma-ray component emerges in the jet so that all the gamma-ray energy contained in it is collimated to flow in a narrow angle. In this way, only some fraction of the supernova energy is required to be channeled into gamma rays.

With this picture in mind, Lifan and I were among the first to argue that the huge energies deduced for the very distant gamma-ray bursts was an artifact of assuming that equal energy is emitted in all directions, rather than being confined to the direction of the jet, as in the blazar picture described earlier. To reduce the required energy from the amount deduced in an “all directions” picture to some fraction of a supernova energy, the jet must be tightly collimated. The area of its cross section must be only one part in a thousand of the area surrounding the burst source. We noted that this is about the amount of collimation seen in typical jets from active galaxies, so it was not beyond the bounds of credibility. Whether it is produced in a real supernova is another story that is the subject of intense investigation, as outlined in Chapter 6.

If the jet moves at nearly the speed of light, the gamma rays will be blue-shifted and beamed strongly in one direction. This component could, in principle, be seen at cosmological distances if the jet happens to be pointed right at the Earth. Most of the jets will not be pointed at the Earth, so this picture requires many more gamma-ray burst events that are not pointed at the

Earth to account for the few that are. If the collimation is to one part in a thousand, then there must be one thousand jets not pointed at the Earth for every one that is. The required rate of bursts is roughly that for normal supernovae, approximately one per few hundred years per bright galaxy, giving a crude concordance to the argument.

While our reasoning was on the right track, the afterglows themselves produced the direct evidence that the energy flow is, indeed, strongly collimated but probably not quite as much as we speculated. The important evidence is that, even though some of the afterglows fade roughly inversely with time as expected for spherical relativistic blast waves, a few were observed to decline more rapidly. The explanation for this behavior requires the invocation of a jet-like, rather than spherical, flow. A critical difference between a jet and a spherical blast wave is that, when it slows down, a jet can expand sideways. This sideways expansion can tap the energy of the jet and cause more rapid cooling and deceleration and hence a more rapid rate of decline of radiation output.

By now many burst afterglows have been analyzed and shown to reveal this behavior. Quantitative analysis by many people, including my colleague, Pawan Kumar, is consistent with their being collimated to only 1 percent of the sky, or even less, somewhat greater than what Lifan Wang and I guessed. This means that the energy is reduced by a factor of 100 or more, and that they must be 100 times more common than the actual rate of detection, about one per day, would imply. When this strong collimation was invoked for GRB 990123, the energy deduced for it was reduced from a mind-boggling level equivalent to the expansion energy of three thousand supernovae to about 10 percent of the total collapse energy of a neutron star, only ten times the expansion energy of a normal supernova. A new phrase entered the literature, the "isotropic equivalent" energy. The idea was that this was the fictitious energy that would have been emitted if the burst radiated equally in all directions – isotropically. The isotropic equivalent energy was a convenient measure of the *apparent* energy, but not to be confused with the *actual* energy emitted, the error made in the first blush.

Armed with this insight, people revisited the issue of the energy of the whole sample of gamma-rays bursts where adequate data was available, the best data involving the time behavior of all the radiation bands from radio to optical to X-ray. The remarkable result was that the rather wide spread in isotropic equivalent energy collapsed to a rather narrow distribution of actual energy emitted. It appears that all the bright gamma-ray bursts have an energy that falls within a rather narrow range (within a factor of a few), an energy that is comparable to, but somewhat less than the kinetic energy, the energy of motion, of a typical exploding supernova. This energy is 100 times less than the total energy released in neutrinos in core collapse, making it actually an interestingly small number, not a challengingly large one. The bottom line is that while gamma-ray bursts remain amazing and mysterious events, their energy is rather modest by supernova standards.

It is now generally accepted that many if not most gamma-rays bursts and their afterglows are jet-like. There are, however, other explanations for the rapid decline of the light of afterglows. If gamma-ray bursts arise in massive stars, as discussed in the next section, then they should be surrounded by the matter blown off in a stellar wind (Chapter 2, Section 2). Even a spherical blast wave would collide with this wind and slow more rapidly than if it only interacted with the dilute matter of the interstellar medium. This interaction can also account for the rapid declines seen in some afterglows. There is, of course, nothing to prevent a jet from colliding with a wind, and if the source of gamma rays pumps out energy for a prolonged time, the tendency for the power to decline can be overcome, so there are lots of complications to be pursued and understood.

1.4. Supernovae and Gamma-Ray Bursts

The third major achievement of the afterglow revolution, after proof of cosmological distances, and discovery that the relativistic outflow is a collimated jet, was the connection of gamma-ray bursts to supernovae. The discovery of the galaxies that were host to gamma-ray bursts also brought suspicion that they were related to massive stars. The gamma-ray bursts were neither far out in the host galaxies, nor in the centers where active nuclei might lurk. Rather they seemed to be in regions of active star formation. This provided circumstantial evidence that they were related to massive stars and hence, perhaps, to core collapse supernovae. In the onrush of events that followed from the *BeppoSAX* discoveries, another surprise made the relation of gamma-ray bursts and supernovae explicit.

On April 25, 1998, *BeppoSAX* discovered a gamma-ray burst, GRB 980425, of otherwise ordinary properties in terms of its apparent brightness, energy, and time scale. *BeppoSAX* then swung to bring its fine position sensor X-ray detector into position and detected a couple of X-ray sources, one of which diminished in time and one of which seemed to be constant. A day later, optical astronomers caught up and found a strongly variable object. This object was not, however, the afterglow that one had quickly learned to expect. It was, rather, a supernova, one of rather strange properties. The supernova, SN 1998bw, was not exactly at the position of either of the two X-ray sources first reported by *BeppoSAX*. This raised some question about the association of SN 1998bw with GRB 980425. In the next few months, the *BeppoSAX* team recalibrated the positions of the X-ray sources they detected. The source that was at first observed to vary was determined to be much too far from SN 1998bw to be associated. The other source, at first thought to be constant, was shifted so that an association with SN 1998bw could not be ruled out. Then this source was discovered to be variable, if only slightly. This has left the issue of the association of SN 1998bw with the *BeppoSAX* X-ray sources somewhat befuddled. One must be wary of other sources of variable X-ray emission, such as active galactic nuclei that could accidentally fall near the supernova, but an association of one of the X-ray sources with SN 1998bw cannot be ruled out.

A few days after the detection of SN 1998bw, Dale Frail of the National Radio Astronomy Observatory at Socorro, NM, Shri Kulkarni at Caltech, and their colleagues found a very bright radio source. This radio source was precisely at the position of SN 1998bw, so there was no question of their association. Analysis of the radio data showed that the radio source was brighter than could be easily explained without expansion of a shock wave at nearly the speed of light. Independent of the gamma-ray burst, SN 1998bw clearly produced a relativistic blast wave. All this evidence taken together suggests that SN 1998bw and the gamma-ray burst GRB 980425 are one and the same thing. The likelihood of finding both GRB 980425 and SN 1998bw in the same part of the sky in the brief interval of time when they erupted is very low, so most astronomers think the connection must be real. In particular, even though gamma-ray astronomers tended at first to be leery of the association, supernova mavens embraced it with full passion.

Observations of SN 1998bw and its host galaxy showed that it was at a distance of about 40 million parsecs or about 120 million light years. That is a great distance, but far less than, for instance, the 12 billion light years of GRB 971214. At 40 million parsecs, the total energy in the gamma-ray burst is deduced to be much less than that of the most powerful gamma-ray bursts, by a factor of about 1 million. On the other hand, at the same distance, SN 1998bw was exceptionally bright for a supernova. Both of these results are puzzles that have still not been fully assimilated in the ongoing attempt to understand gamma-ray bursts.

Although it is a step along an esthetically ugly path, one idea that emerged from this new event was that there were at least two kinds of gamma-ray bursts, one of very high energy seen at cosmological distances and one of lower energy seen relatively nearby. This is an uncomfortable hypothesis given that the gamma-ray properties of GRB 980425 were seemingly unexceptional. The similar nature of far-away energetic and nearby lower-energy gamma-ray bursts may arise because any physical events that can emit gamma-rays will have certain properties in common whether the total energy involved is high or low, but this remains to be shown. Another possibility that is actively discussed is that these bursts are all basically the same thing, but that the burst looks different, and dimmer, if you look at it from an angle rather than having it aimed right at you.

SN 1998bw brought its own set of questions. The early spectra seemed unlike any other supernovae we have discussed, Type Ia, Ib, Ic, or II. Closer study showed a similarity to Type Ic but with especially high velocity causing an exceptionally large Dopper shift and “broadening” of the absorption features associated with atomic absorption. As it evolved, SN 1998bw looked more and more like a Type Ic with no evidence for hydrogen or helium. It certainly did not look like either a Type II or a Type Ia. With hindsight, there were a few other supernovae, SN 1997ef is a conspicuous example, that did bear some resemblance to SN 1998bw, and there have been a few more since.

The first models of the light curve and spectra of assumed that SN 1998bw resulted from core collapse, and that enough radioactive nickel was produced to power the peak of the light curve. Because SN 1998bw was about as bright as a Type Ia (even though the spectrum is completely different), a comparable amount of radioactive nickel (Chapter 6, Section 6) is required, about 0.7 solar mass. Basic spherically symmetric models can produce this amount of nickel in a core-collapse explosion by shocking silicon layers, but they are extreme. Models that make this much nickel and that produce the observed light curve and spectra at some level of agreement (not perfect in the first models) require an exploding carbon/oxygen core of about 10 solar masses and an energy of expansion of the matter of more than ten times that normally associated with supernovae. These models suggest that SN 1998bw was a “super” Type Ic, and the term “hypernova” has been adopted in some circles. SN 1998bw was certainly exceptional in many ways. Other events labeled “hypernovae” have shown rather high velocities, but normal luminosity for a Type Ic, no relativistic outflow, no radio outburst, no gamma-ray burst. Exactly which events should bear the label “hypernova” is, at least, controversial.

Like Type Ic, SN 1998bw showed signs of asymmetry (Chapter 6), evidence that the flow of ejected matter departs rather strongly from spherical symmetry. This evidence was ignored by the first spherically symmetric “hypernova” models that require unprecedented amounts of energy to provide the supernova luminosity. Peter Höflich, Lifan Wang, and I have considered models that are distorted by a sufficient amount to account for the asymmetries in Type Ic supernovae and in SN 1998bw itself. Preliminary models showed that, if the ejecta are in the shape of a fat pancake, they will be considerably brighter if viewed from the top of the pancake compared to the edge, by about a factor of 2. These models have the potential, at least, of accounting for the observed optical properties of SN 1998bw with “normal” amounts of energy and ejected nickel mass. Whether such models, or the “hypernova” models for that matter, can account for the gamma-ray properties remains to be seen.

The question of the connection of supernovae and gamma-ray bursts was further fueled by developments in the spring and summer of 1999. One gamma-ray burst from 1998 was later found by Shri Kulkarni, Josh Bloom, and their colleagues at Caltech to show evidence for a brightening about 3 weeks after the gamma-ray burst that interrupted the otherwise rather rapid (and hence from a jet?) decline of the afterglow. This apparent new source of light was roughly consistent with the addition of the light from a “SN 1998bw-like” event that reached peak about 3 weeks after the gamma-ray burst, a reasonable time for a supernova to have attained maximum light output after its initiation. After this discovery, the original afterglow event, GRB 970228, was also reanalyzed; evidence for a “SN 1998bw-like” brightening was deduced, and similar arguments were advanced for one or two more events. All this added to the growing circumstantial evidenced that supernovae, most likely some variant of Type Ic and gamma-ray bursts were connected.

Another strong piece of evidence in this direction was the occurrence of GRB 021004. This was the first gamma-ray burst that we successfully observed at McDonald Observatory with the Hobby-Eberly Telescope. Lots of other people got wonderful data on it as well. This burst showed rather direct evidence of material blown out from a massive star in a stellar wind prior to the explosion. This added to the growing conviction that gamma-ray bursts were associated with the death of massive stars.

At this point essentially every major observatory on the planet was engaged in the supernova hunt. The proof came in March of 2003 with GRB 030329. This burst proved to be relatively nearby, only three billion light years away! Right next door compared to the 12 billion light years of GRB 971214. Everyone knew this was a good candidate from which to search for direct proof of the supernova connection. We certainly tried. We knew what to do: look after the gamma-ray burst for evidence of a rising contribution of supernova light and get a spectrum to prove what it was. Unfortunately our telescope was not quite sensitive enough for the task. Other observatories pinned it down, but there it was, just as expected. The early afterglow showed no evidence of a supernova, but about a week later, an extra contribution of light was seen. After the careful job was done of allowing for the still bright light of the afterglow itself, a spectrum was obtained and it was nearly identical to that of SN 1998bw a *bona fide*, if somewhat strange supernova. This was drop-dead proof that this gamma-ray burst arose in the explosion that created a supernova.

One has to be careful not to leap to the conclusion that every gamma-ray burst arises in a supernova, but that is clearly where all the evidence is pointed, at least for certain classes of gamma-ray bursts. The gamma-ray burst and supernova communities have basically accepted this conclusion and are moving on to ask more detailed questions: what supernovae, why, and how?

1.5. The Possibilities

These years of mind-churning progress after the first *BeppoSAX* discovery have left a large range issues concerning gamma-ray bursts that will take more work and ingenuity to resolve. Principal among these is the basic nature of the explosion. What sort of explosion is involved and how is it related to "normal" supernovae? Other, closely related, issues are why the energy is collimated, how it gets out of the star without dragging so much star stuff that it cannot blast relativistically into space. How, exactly, is the blast converted to gamma-rays? While some of the bursts show evidence for the circumstellar matter expected to be expelled in the wind from a massive star, others rather distinctly do not. How can that be, if gamma-ray bursts all come from massive stars? Is there, after all, more than one way to make a gamma-ray burst? Some of the *BeppoSAX* and *HETE 2* events showed optical afterglows, but others did not. Most of the afterglows decay so that the power fades inversely with time, but some decay more rapidly. In a real sense, the field is just beginning and will continue to explode with activity.

A plethora of models have been devised to address the gamma-ray burst energy issue head on.

Some of these schemes involve colliding neutron stars at the end of a long gravitational in-spiral. That process has plenty of energy, enough for the most extreme events if the energy emerges in a jet. Another principal issue is turning the energy into gamma rays and a relativistic blast wave that is not so overloaded with protons that it cannot move rapidly enough to make the burst or the afterglow. One possibility that has been discussed is that the neutron stars do not collide directly but interact through their strong magnetic fields. That way one can think about turning the pure magnetic energy into pure gamma-ray energy without getting the stuff of the neutron stars, those troublesome, slowing baryons, directly involved. The problem with that class of models is that neutron stars require a long time to spiral together under the grip of gravity waves, so they are expected to have drifted farther from the star-forming regions of host galaxies then gamma-ray bursts are observed to do. Such a model might still account for some fraction of observed gamma-ray bursts.

Other models invoking neutron stars suggest that the powerful radiation from a newly born pulsar could result in a gamma-ray burst. These models have the possible advantage that they are the smallest step away from "normal" supernovae. In addition, as discussed in Chapter 6, we have found that normal supernovae that are most likely to involve neutron star (rather than black hole) formation are asymmetric and might involve jets. Gamma-ray bursts seem to occur less frequently than core collapse supernovae (but see the next section), so it must be the rare supernova that makes a burst. On the other hand, the highly magnetized magnetars (Chapter 8, Section 10) are more rare than ordinary pulsars. We do not know what the birth event of a magnetar is like; could that also be the rare explosion that produces a gamma-ray burst?

I have written a several of papers on this topic, analyzing the capability of a new born neutron star to produce magnetic jets in normal supernovae, in extreme events like SN 1998bw and even, perhaps, gamma-ray bursts. In one paper, we envisaged a neutron star spinning like a pulsar with a simple dipole magnetic field, with the magnetic axis tilted with respect to the spin axis (Chapter 8, Section 2). Then we realized that when it is first born, the field is likely to be wrapped around the equator like a doughnut. In a paper with Dave Meier, a magnetic jet expert from the Jet Propulsion Laboratory and Jim Wilson, a pioneer of supernova collapse calculations in general and magnetic collapse in particular, we analyzed how a torus of field might make a jet and explosion. We envisaged that there might be a first jet when the neutron star first forms that explodes the star, that would be a normal supernovae. In some cases, however, we imagined that the subsequent rain of material crushes the neutron star to a black hole and that launches a second, even faster jet that catches up to the first and creates the gamma-ray burst. A possible advantage of this picture is that both jets could be full of magnetic field that must be there to make gamma-ray bursts radiate as they do, but the origin of which is not well-explained.

The most popular model to account for the production of gamma-ray bursts involves the collapse to form a black hole. This has also been termed the "collapsar" model, a word coined by Stan Woosely of the University of California at Santa Cruz who has advocated such a model with great vigor. Strictly speaking, a stellar collapse could yield either a neutron star or black hole, but in its popular usage, *collapsar* means the generic class of models based on black hole formation.

Woosley and his colleagues envision collapse to form a spinning black hole. Subsequent infall forms an accretion disk of matter around that black hole. The accretion energy is assumed to be channeled up the rotation axes by the natural axial nature of the rotating geometry or perhaps with the collimating aid of twisted magnetic fields. A jet of energy with plausibly sufficient energy and the capability of emerging relativistically into the surrounding space could be generated.

The appeal of this class of models is clear. Gamma-ray bursts are extreme events and black hole formation is an extreme event. We commonly see relativistic jets emerging from supermassive black holes in active galactic nuclei (Chapter 10, Section 9), so the parallels are compelling. In addition, detailed numerical models can account for various aspects of the problem, the formation of jet-like flow from the vortex around the black hole, the propagation of a jet out through the star with sufficiently large energy but small baryon load that it can emerge and accelerate to something like observed gamma-ray burst speeds.

Nevertheless, as in other contexts, invoking something as exotic as black holes requires a high standard of proof, and that proof is not yet forthcoming for gamma-ray bursts. The black hole explanation also brings some conundrums of its own. We do not know exactly what mass stars collapse to make black holes, but we suspect it is moderate, perhaps around 30 solar masses. Even allowing for the fact that we probably witness only one out of a hundred gamma-ray bursts because the others are aimed away from us, the rate of formation of gamma-ray bursts seems to be significantly less than the rate of death of 30 solar mass stars. That would suggest that not every collapse to form a black hole yields a gamma-ray burst. We need to understand why that is so. Black holes seem plausible because they can, in principle, provide a huge energy, but there is a puzzle of just the opposite sort. With collimation, we know that the typical energy in gamma-ray bursts is somewhat less than the typical expansion energy of a supernova and a factor of over one hundred less than the gravitational or rotational energy associated with formation of a black hole. How is it that such a small, and yet well-defined fraction of the total reservoir of energy available is channeled into the gamma-ray burst?

There are also theoretical issues remaining to be resolved. There is a general perception that if a black hole launches a jet, that jet can both explode the star and produce the gamma-ray burst. That is not at all clear. For the jet to make a gamma-ray burst it must be thin and fast to penetrate the star without slowing down too much. That means it cannot interact with the star very much and that means it cannot explode the star. The analogy we invented in the paper by Wheeler, Meier, and Wilson referred to earlier is like shooting a needle through a loaf of bread. The needle could penetrate without perturbing the loaf. How, then, does the star explode as a supernova? It could be that the "standard" processes of neutrino transport (Chapter 6, Section 4) do the trick, but that is far from proven, even for normal supernovae and certainly in the case when a black hole, not a neutron star, forms. It also remains far from firmly established exactly how a new born black hole produces a jet and under what circumstances that jet will have the right properties to be a gamma-ray burst. The role of magnetic fields in this process have scarcely been addressed.

People are addressing these issues. There are a number of interesting papers discussing black hole formation is a variety of contexts, from single stars, or, even more interesting, from various binary systems. Some of thes models involving swallowing the black holes in common envelopes of normal stars or of helium stars as might be the progenitors of Type Ib or Type Ic supernovae. An advantage of the binary models is that they have some promise of spinning up the progenitor star and thus providing an especially rapidly spinning black hole, a seeming requirement for a successful gamma-ray burst model. This special requirement might also help to explain why not all black hole formation yields a gamma-ray burst.

Other suggestions have problems as well. A key one for any model based on neutron stars rather than black holes is the danger that a jet emerging from near a neutron star would be far more contaminated with neutron rich matter than observations allow.

All these pictures have a certain basic plausibility about them, given that we think our Universe is full of magnetic neutron stars and black holes of a range in mass from those of stars to those of galaxies. The devil is in the details. Having accounted for the energy, the first major requirement, can any of these models really account for gamma-ray bursts with the observed properties? All these models that are designed to give very high energy gamma-ray bursts at cosmological distances must also confront GRB 980425 and SN 1998bw. How is it that a newly formed accreting black hole in the young Universe produces a gamma-ray burst with the same average observed properties as a relatively nearby, much less energetic, odd supernova?

I have written some papers exploring the question of whether or not gamma-ray bursts are related to the formation of neutron stars, in part just to keep this option on the table. If I were to bet, I would bet on some form of a black hole model. To my mind, resolving this issue is the biggest problem remaining in gamma-ray burst research. Just what is the nature of the gamma-ray burst machine and how do we prove they involve black holes if that is, in fact, what they are?

1.6 The Future

The latest wrinkle in this area comes from an exciting new development in the study of soft gamma-ray repeaters (Chapter 8, Section 10). Gamma-ray bursts divide into two distinct categories, most last about 30 seconds, as described earlier. A significant minority, however, last less than a second; a few tenths of a second is typical. Another puzzle of gamma-ray burst research has been to understand this dichotomy in temporal behavior. Does this represent variations on a theme, or two distinct physical processes? In September 1999, one of the soft gamma-ray repeaters produced a gamma-ray burst that was indistinguishable from the "short" gamma-ray bursts. Because the soft gamma-ray repeaters are highly magnetic neutron stars or magnetars (Chapter 8, Section 10) in our Galaxy, this raised the question of whether or not all the short gamma-ray bursts could from neutron stars in our Galaxy. If this is so, their distribution should not be uniform on the sky because of the Sun's offset position from the center of the Galaxy. For technical reasons, *BeppoSAX* could not respond to these short bursts, so everything that has been learned about gamma-ray bursts and their afterglows in the *BeppoSAX* era pertained only to the "long" gamma-ray bursts. *HETE 2* had the capability in principle to detect and study the short bursts but did not manage to elucidate the issue.

The latest chapter in this particular saga happended on December 27, 2004, while the new *Swift* satellite was still in its check-out phase. Another Galactic magnetar let off a huge burst of energy, 100 times brighter at its peak than the one mentioned above. *Swift* saw this burst, but *Swift* was not needed: this burst "pinned the needle" on something like 15 other space craft from Earth orbit to Mars. Once again this burst temporarily rattle the ionosphere of the Earth even though it came from 50 thousand light years away, on the far side of the Galactic center from the Earth. Some of the radiation even reflected off the Moon.

This burst only lasted 0.2 seconds, so it would not have been confused with the "long" gamma-ray bursts that have been the focus of this chapter. That time scale put it, however, in the range of the "short" bursts. The teams of astronomers who analyzed the data, including my colleague Rob Duncan, deduced that such a burst could be easily be observed to great distances. They concluded that the *BATSE* sample of short bursts almost surely contained such magnetar bursts, perhaps half of all the short bursts it saw. The conclusion still seems to be that such bursts cannot account for all the short bursts, so this story is yet to fully unfold. *Swift* will play a key role here, as it was designed to do. *Swift* should be able to observe these magnetar bursts to great distances and discover several a year. *Swift* has already seen several short bursts, but there was no host galaxy in the direction of the sky, so these must have been the "other" non-magnetar bursts, the source of which remains a mystery.

These are the conundra that make astrophysics so exciting. Gamma-ray bursts will continue to provide all the stimulation an astrophysicist could want for some time to come. As better understanding of the gamma-rays bursts develops, so will a better understanding of the Universe on both stellar and cosmological scales. The gamma-ray bursts give us yet another means to look throughout the space and time of our visible Universe.

BATSE detects about one gamma-ray burst per day. If every one were like GRB 990123, there should be a bright optical flash for a minute or so once a day somewhere on the sky that would be easily visible with a decent pair of binoculars. A pair of binoculars allows you to see about one part in a thousand of the total sky. If you looked every night for 3 years running, you just might get lucky. Here comes backyard cosmology.

If this interpretation of the observations in terms of exceptionally high ejected mass and exceptionally high explosion energy is right, then SN 1998bw is an exceptional event. It must involve processes unlike all the other supernovae discussed in this book. Speculations run toward the creation of a black hole in the explosion and subsequent accretion of matter to fuel the large energy release. Another possibility is that the explosion is asymmetric so that the explosion looks brighter at some viewing angles than others. All these possibilities need to be explored.

USE? WHERE?

Could SN 1998bw possibly be related to other more normal Type Ic despite the evidence for very high ejecta masses and high explosion energies? There is evidence that “ordinary” Type Ic are not spherically symmetric but that they produce explosions that are distorted in a significant way. This already suggests that the core collapse that generates Type Ic, and presumably all other collapse-driven supernovae, is strongly asymmetric, perhaps involving jets shooting out the rotation or magnetic axes. Could such events be brighter in one direction than another, accounting for the apparent excess luminosity of SN 1998bw? Is the evidence for nonspherical ejection in Type Ic related to the jets necessary to make gamma-ray bursts that can be seen across the Universe? If soft gamma-ray repeaters require magnetars (Chapter 8), neutron stars with superstong magnetic fields, what happens at their birth? Are magnetars born in binary star systems that spin up the star? Do they generate a jet when they form? Do they resemble Type Ic supernovae or SN 1998bw? These are all questions that need to be addressed.

X-ray flashes

Swift

Cosmology

1.6. The Past in Our Future: The Dark Ages

Looking to the future brings yet another exciting possibility. After the epoch when the Universe was a million years old, the cosmic radiation streamed freely. The matter cooled and became dark. During the subsequent eons of expansion, the matter agglomerated into lumps that became galaxies. At some point, the gas in the lumps condensed and heated and started the first production of stars. The long interval between the release of the cosmic background radiation and the lighting up of the first stars has come to be called the “Dark Ages.” After a long period with no light, stars winked on and the Universe started to take the form we recognize around us now. The processes involved in forming the first stars and galaxies, the emergence from the Dark Ages, is one of the frontiers of modern astronomy. It can be probed by the new generation of telescopes in the 8- to 10-meter class. The end of the Dark Ages will be the prime target of the *Next Generation Space Telescope* currently under design by NASA.

Some of those first stars to form will be massive. They will evolve, collapse, and explode in just the way described in Chapter 6. When they do, their host galaxies will still be embryonic, small, and dim. There is a chance that, when astronomers peer back to the beginning of the end of the Dark Ages, they will see supernovae, the brightest beacons in the young Universe.

The first supernovae to arise should be from massive, short-lived stars. They should be predominantly Type II supernovae, although there could also be an admixture of Type Ib and

Type Ic supernovae. The Type II supernovae might all resemble SN 1987A by exploding as blue supergiants. As explained in Chapter 7, we do not fully understand why SN 1987A was a blue rather than a red supergiant when it exploded. Theoretical studies have shown, however, that when the amount of heavy elements in the atmosphere of an evolving massive star is low, the hydrogen envelope is likely to remain relatively compact so the star will look hot and blue rather than expanding so that the star will look cool and red. In the very young Universe at the end of the Dark Ages, there will not have been much time to make heavy elements. Whatever caused SN 1987A to be a blue supergiant, the paucity of heavy elements in the young Universe may cause all the exploding stars to be blue supergiants, even if they retain their hydrogen envelopes against the ravages of winds and binary companions.

If the first supernovae at the end of the Dark Ages explode in blue supergiants, the resulting explosions, like SN 1987A, may be relatively dim and somewhat harder to see. As the Universe ages and more heavy elements collect in the interstellar gas from which new stars are born, then at some point, massive stars may begin to evolve into fully formed red supergiants before they die. They will then explode as what we consider to be "normal" Type II supernovae. With the full power of new telescopes to scan from the present epoch back to the end of the Dark Ages, we should be able to see that epoch when the normal Type II supernovae turn on.

This discussion has omitted Type Ia supernovae. That is because we think they have a "fuse" that must burn before they explode. As discussed in Chapter 6, we do not understand the binary evolution that leads to the explosion of a white dwarf as a Type Ia supernova. All the indications are, however, that considerable time must pass before these binary processes, perhaps the evolution of the smaller-mass companion, perhaps the decay of orbits through emission of gravitational radiation, lead to the explosion. That Type Ia supernovae have a long fuse compared to Type II means that when supernovae begin to explode at the end of the Dark Ages, they should all be due to the collapse of the cores of massive stars. There should be no thermonuclear explosions of white dwarfs and hence no Type Ia.

As the Universe ages and the binary evolution fuse burns, there will eventually be an epoch when the Type Ia supernovae begin to explode. Using the big new telescopes on the Earth and in space as time machines to probe these distant times, we should also be able to see this onset of Type Ia events. This would be a very exciting result because the time of the onset will give us critical new information on just what type of binary evolution constitutes the fuse. This, in turn, may finally teach us what binary evolution leads to Type Ia.

Mention JWST