The Biggest Bangs

The Mystery of Gamma-Ray Bursts,
The Most Violent Explosions
in The Universe

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Chapter 16

The Holy Grail

A few miles from Los Alamos, New Mexico, stands one of the most remarkable astronomical observatories in existence, the Robotic Optical Transient Search Experiment (ROTSE). It is completely automated, steered by electronic signals received over the Internet. Housed in a military surplus hut (purchased from a scrap dealer) the size of a large closet, it consists of a cluster of four commercial telephoto camera lenses (200 mm focal length, f/1.8), each about four inches in diameter. Made by Canon, they can fit on an ordinary Canon 35 mm camera. At $4,199 apiece (in 1995), they were too expensive for most amateurs, but just right for the professional sports, nature or news photographer. Each lens feeds light to a CCD (charge-coupled device, an integrated circuit which converts a visible image to electrical signals) camera, very similar to the CCD in an ordinary digital camera. Each CCD divides its image into about four million picture elements, an impressive figure in 1995 but one which consumer digital cameras are now approaching. An obsolescent 133 MHz PC, running the Linux operating system (for reliability Windows just won't do) controls each CCD. If it weren't bolted to a mount, you could pick up the entire telescope and camera array and carry it off under your arm. On January 23, 1999, one of these four cameras recorded visible light from a gamma-ray burst as it was happening, which had been the holy grail of gamma-ray burst astronomy for a quarter of a century.

From the discovery of gamma-ray bursts, astronomers had asked themselves if the gamma-rays were accompanied by visible light, and if this light could be detected. Because there was no theoretical understanding of bursts, or even a model which could be calculated in detail, it was not possible to predict how bright their visible counterparts would be. However, if even a tiny fraction of the gamma-ray energy appeared in visible light they would be quite bright. Analogy to known bursting X-ray sources suggested that this fraction might be between 0.1% and 1%. If gamma-ray bursts were found in binary stars, one of the most popular early theoretical ideas, gamma-rays would be absorbed in the atmosphere of the companion star and roughly 0.1% to 1%, the exact percentage depending of the distance to the companion, its size and properties and the gamma-ray intensity, reradiated as visible light. In fact, this is exactly what happens in X-ray bursters.

This is not a very large fraction—you hardly notice it when the sales tax is raised by 0.1%, and most investors happily accept that the managers of their mutual funds and other investments rake off about 1% of their assets every year in fees and expenses. Yet if 1% of the energy of a bright, but not extraordinary, burst (a "burst of the month") were converted to visible light it would be about 6th magnitude. That is visible by a good naked eye in a dark sky, and is extremely bright by the standards of professional (or even serious amateur) telescopic astronomy.

Of course, you would have to know when and where to look. Ay—there's the rub, because gamma-ray bursts are unpredictable. There are two possible approaches to this problem. One is to use the direction to the burst, determined by the gamma-ray observations, to steer the optical telescope. Unfortunately, data analysis was slow, and positions measured by the Vela satellites, and the later interplanetary networks, did not become available until weeks or months after the bursts. The other approach is to design an optical system, using a form of fish-eye lens, which collects light from as much of the sky as possible. Then, if a flash were detected and recorded, the optical data could be compared at leisure to gamma-ray data to see if they occurred in the same place on the sky and at the same time. If no flash were seen, it would at least be possible to set an upper bound on how much visible light was emitted by any gamma-ray burst in the portion of sky under observation.

There was also the hope of discovering some completely new phenomenon which might make flashes of visible light alone, without gamma-rays. For example, an event like a gamma-ray burst, but with lower Lorentz factor (more baryon poisoning), might radiate most of its energy as visible light rather than gamma-rays. Or, there might be something completely unrelated to gamma-ray bursts. New phenomena are generally discovered by new instruments with new capabilities. That is how gamma-ray bursts themselves were discovered, as well as pulsars, radio galaxies, the cosmic background radiation and even the expansion of the Universe. Fame and prizes, the chief motivators of scientists, are the rewards for discovering something really new.

The performance of any optical system is governed by certain laws, the most important of which is called Liouville's theorem. In essence, it states that if an optical system (a telescope, or a camera) is to have a large field of view, the range of angles from which it collects light, it must be small. A telephoto lens, with a comparatively small field of view, may be larger than a standard camera lens, which in turn is larger than a wide field of view (fisheye) lens. An ordinary astronomical telescope is really only a camera with a very large telephoto lens, or a mirror which takes the place of a lens.

Just how small an optical system must be depends on the size of the device which records the light, onto which the light is focused. Modern astronomical systems use CCDs because they are very efficient, recording nearly all the visible photons falling onto their surface (in contrast to photographic emulsions, which record less than 1%), and because their electronic data are easy to process by computer. Unfortunately, CCDs are generally no more than an inch square.

For the astronomer looking for faint objects, this means that if he is to detect them over a large swath of sky his collecting lens or mirror must be small. It won't collect very much light, and the instrument won't be very sensitive. In addition, each picture element of his detector will receive light from a broad area of sky, including whatever stars and stray light there are, making it difficult to observe faint flashes against this background. The more picture elements into which he can divide his field of view, the less of an obstacle the background will be, and the more sensitive will be the instrument. Increasing the number of picture elements is the chief goal of CCD manufacturers; if it were easy, it would have already been done. This is the reason ROTSE uses four separate lenses and CCDs, for a total of sixteen million picture elements. More would have been even better, but the budget was limited.

If the entire sky must be monitored for possible visible bursts the astronomer needs as big a field of view as possible. It is not necessary that he detect every burst, and he cannot come close. Some will be below the horizon, or in the haze near it. Others occur in daytime, or twilight, or in moonlight (a serious source of background light), or in bad weather, or behind the thick clouds of dust and soot which fill the plane of our Galaxy. Combining these factors means that, at best, a single observatory can see about 3% of the bursts which occur, or about one per month, most of which are weak. The astronomer cannot afford to lose many more, so his instrument must have a field of view which encompasses most of the sky. Liouville's theorem then implies that his collecting lens cannot be larger than the CCD which records the data, perhaps an inch in diameter, and may be even smaller. He must do research with a lens smaller than that in a child's toy telescope. Multiple lenses and CCDs help, but multiply the cost, too.

This sounds hard, and it is. The first proposal to monitor the sky for optical counterparts of gamma-ray bursts was made by Paul Boynton of the University of Washington in 1974, not long after the bursts themselves had been discovered. Boynton was trained as a physicist, but moved into astrophysics, studying pulsars, especially those which flash in visible light, and was uniquely well suited to search for optical transients. CCDs were not yet available, so he proposed to use the best technology of the time, a vacuum tube imaging device called a vidicon. It would have only 25,600 picture elements, but he still predicted it would be able to detect 10th magnitude flashes lasting a second. In fact, he planned to use two telescopes some miles apart as a stereo camera, so that he could tell whether a flash was nearby (a meteor, or the sun reflected by an artificial Earth satellite) or distant, like a gamma-ray burst. He also planned on completely robotic operation, necessary to keep the costs reasonable, and every subsequent proposal has followed his lead. Boynton's proposed instrument would have been more than sufficient to detect the 6th magnitude flashes suggested by a naïve guess of 1% gamma-ray to optical conversion. In fact, it might have detected a 9th magnitude flash like that finally observed in 1999. Promises of instrumental sensitivity have a history of being overly optimistic, but the development of CCD technology would have improved the sensitivity over the original design.

After working out the parameters and rough design of his detector system, and publishing them in the proceedings of a conference, Boynton submitted a formal proposal to the National Science Foundation for support to pay for its construction. The NSF rejected his proposal, citing a referee who said he had "failed to show that [they] would, in fact, observe anything." Of course, if they had known in advance what they would discover, it would not be a discovery. The proposed instruments were unprecedented, and only possible because of advances in technology. It was easy for unimaginative reviewers to attack such a proposal. The reviewing process invites attacks, and even one negative opinion out of five or six reviews is usually sufficient to ensure rejection. Had this proposal been approved, the visible counterparts to gamma-ray bursts might well have been discovered twenty years earlier than they actually were, and the nature of the bursts understood much sooner.

Boynton gave up on gamma-ray bursts, and went on to a successful career in X-ray astronomy and fundamental physics. The subject of optical counterparts went to sleep until the early 1980's, when Schaefer, examining archival photographs, reported finding bright transients at the positions of bursts, but decades before the bursts themselves (Chapter 8). This revived interest because his results seemed to imply optical counterparts of 6th magnitude or brighter, which appeared readily detectable. A number of instruments were proposed, and some of them actually built. The best known were the Explosive Transient Camera (ETC), developed by a team led by George Ricker at MIT, and the Rapidly Moving Telescope (RMT), a project of the NASA Goddard Space Flight Center under the leadership of Bonnard Teegarden. Preliminary designs and plans were announced in 1983.

These two instruments were designed to work together, automated and unattended. The ETC would stare at a large swath of sky, waiting for flashes of light. Once a flash had been detected, its position would be transmitted to the RMT, a much larger telescope (originally planned to be seven inches in diameter, compared to about one inch for each of the sixteen individual lenses in the ETC), with a small field of view and greater sensitivity, which would steer to the position of the flash in a few seconds. Astronomical telescopes usually have plenty of time to move from one target to another, which is called slewing, because most astronomical objects are permanent, available to be studied whenever convenient for the astronomer. A telescope will generally point at one target for many minutes at a time, gradually accumulating light from a faint star or galaxy, and only moving to follow the rotation of the Earth (which makes everything in the sky rise and set like the Sun). Slewing to the next target in a hurry is not usually important.

Rapid slewing would be essential to the RMT. By turning to the position of a flash in a few seconds or less it would catch a burst as it happened, collecting much more accurate data than the tiny ETC. The ETC, detecting the visible counterpart of the burst and providing approximate but timely coordinates, would take the place of a gamma-ray burst detector in space which could determine burst coordinates and radio them to an optical telescope, in "real time", while the burst was still going on. The RMT would also produce a sharp image of the transient. This would not show any detail—gamma-ray bursts were much too distant, in anybody's model, for that. It would give a precise position, accurate to about two arc-seconds, which could later be used to steer a large telescope to the position of the burst and see what was there, perhaps a faint star in our Galaxy or a distant galaxy.

The ETC, originally planned to be operational by 1985, was a long time coming. Funding was limited (the NSF rejected a proposal to support its development, too). Many novel technologies, particularly information processing algorithms and communications protocols, needed to be worked out. One ETC finally began collecting data in 1991, a few months before the launch of GRO and BATSE. When finally completed ETC had a much smaller field of view than originally planned. Instead of staring at 43% of the sky above the horizon, it only stared at 12% (at an intermediate stage in its development the figure was down to 6%). This nearly four-fold reduction meant a corresponding reduction in the rate at which gamma-ray bursts would occur within its field of view. Making the usual allowances for daytime, weather, Galactic absorption, twilight and moonlight meant that it could only observe about $\frac{1}{2}$ % of whatever flashes there are. Either because this fraction was so small, or because it was not sensitive enough (it was estimated to be able to detect one second flashes as faint as 7th or 8th magnitude, although it was originally hoped to be able to detect flashes down to 11th magnitude, more than twenty times fainter), ETC never found any convincing evidence for visible flashes.

ETC found an enormous number, hundreds per night, of spurious flashes, mostly sunlight reflected by artificial Earth satellites, meteors, clouds scattering moonlight or stars appearing from behind clouds. Had there been two ETCs, operating as a stereo pair as originally planned, the spurious flashes could have been eliminated in real time, and the positions of any genuine flashes (as well as the few spurious flashes not so easily eliminated) handed off to the RMT. Because there was only one ETC the discrimination of spurious flashes could only be done "off line", after some delay, too late to save the RMT from chasing a large number of spurious events. It may be possible to find a needle in a handful of straw, but ETC was giving the RMT a whole haystack. As a result, the RMT never collected useful data.

A fortuitous failure on the Gamma-Ray Observatory soon made ETC, and all similar sky-staring telescopes, obsolete. As originally designed, all instruments on GRO, including BATSE, would record their data on an on-board tape recorder. Several hours of data would be accumulated and then transmitted to the ground over NASA's system of Tracking and Data Relay Satellites (TDRS). Not long after the launch of GRO its two tape recorders (the principal one, and its backup) began to fail. This became worse and worse, until they became unusable in early 1992, before the satellite had been in space for a year.

It would have been easy simply to declare GRO a complete loss, and to shut it down, but this time NASA did the right thing. A new ground station for the TDRS system was built and installed, first in Guam and later in Australia. This enabled data to be relayed to the ground as they were received (in real time), without any significant delay. The scientists could see the data coming in as a gamma-ray burst was happening.

Scott Barthelmy of NASA's Goddard Space Flight Center recognized this as an extraordinary opportunity. The BATSE data included not only the brightness and spectrum of a burst, but also its position on the sky. By design, and because of the technology used in BATSE, these positions were very approximate (the error circles were believed to be between four and ten degrees in radius), but they were accurate enough to permit a ground based telescope to be pointed in that direction. In a stroke both ETC and RMT became obsolete, ETC because BATSE was now providing gamma-ray burst positions directly, without depending on the initial detection of an optical flash and verification of it as a genuine cosmic event, and RMT because its field of view was much too small to view more than a tiny fraction of the entire BATSE error circle.

Barthelmy seized this opportunity by constructing the BATSE Coordinates Distribution Network (BACODINE, later renamed the Gamma-ray burst Coordinate Network, or GCN) to distribute the information from BATSE. He did this entirely on his own, without funding from NASA, scrounging and "bootlegging" resources as necessary. When finished, NASA management was amazed how quickly and economically it was done, for had it gone through a formal planning process it would have cost several hundred thousand dollars and taken much longer.

By the middle of 1993, about eight months after the original idea, BACODINE was up and running, calculating burst positions from BATSE data and distributing them over telephone lines. In a few more months Internet and e-mail distribution was added. Any astronomer or observatory, anywhere on Earth, could now learn the coordinates of a burst within about five seconds of its detection by BATSE. The majority of bursts would still be going on.

Barthelmy's ambitions were not limited to distributing coordinates. He realized that the coordinates, by narrowing the field of view which needed to be monitored, would make the detection of a simultaneous visible counterpart much easier. Instead of looking at as much of the sky as possible it would be sufficient to slew a telescope to the position indicated by BATSE. The required field of view would still be very large by astronomers' standards (8 to 20 degrees across), but much smaller than that required to stare at the entire sky. The instrument could have a much larger lens which would collect more light, and it could be much more sensitive. Essentially, it would be a hybrid of the ETC (itself, following Boynton's 1974 design principles) and the rapidly slewing RMT, with a field of view and optical design intermediate between these two instruments. It could be thought of as a modified RMT using BATSE and BACODINE in place of the ETC.

He called his proposed instrument the Gamma-ray to Optical Transient Experiment (GTOTE). Together with BACODINE, it might have enabled him to discover the first simultaneous optical counterpart of a gamma-ray burst. Unfortunately, it was not supported by NASA, and was never completed.

Gamma-ray burst astronomers were not the only scientists needing wide field of view optics. In the 1980's the U. S. Strategic Defense Initiative, popularly known as Star Wars, was looking for ways to detect and track missile launches and re-entering warheads from space. Brilliant Pebbles was a scheme to destroy enemy rockets and warheads by smashing a solid body into them (an earlier version had been called Smart Rocks) and it needed accurate tracking. One of the methods considered was optical imaging. A wide field of view would be required because a threat could come from a broad range of directions.

The Lawrence Livermore National Laboratory is a large institution (with about 7,000 employees, roughly half of them scientists, engineers and programmers) run by the University of California in Livermore, California, 40 miles east of San Francisco. Its chief mission is nuclear weapons (it is a sister to the Los Alamos National Laboratory, where the first atomic bomb was developed), but it also engages in many other kinds of defense research, in addition to a substantial program of basic research unrelated to defense. In the late 1980's Livermore received a contract to develop a Wide Field of View Camera for space defense. Hye-Sook Park, trained as an experimental particle physicist, led its development. Brilliant Pebbles then ran into trouble, and Livermore's Wide Field of View Camera gathered dust.

Carl Akerlof is an experimental particle physicist at the University of Michigan (where Park had been a student). During the 1970's and 1980's particle physics experiments grew to require ever larger teams, in some cases consisting of several hundred scientists. This reduced the independence and opportunities for initiative of all participants, and he looked to observational astrophysics for science on a smaller and more human scale. He became involved in an experiment (Whipple) observing high energy gamma-rays, using the Earth's atmosphere as a detector, a technique very similar to those of particle physics, and in MACHO, which uses optical telescopes to study dark matter in our Galaxy by observing gravitational focusing (microlensing) of the light of distant stars by the dark matter.

In 1992–1993 Akerlof came to Berkeley for a year's sabbatical leave (a temporary appointment on the faculty of another institution) because the MACHO project was led by Livermore with a large Berkeley contingent. He went to Livermore to visit Hye-Sook Park, whom he had known slightly from her student days. Akerlof had earlier become interested in the problem of searching for optical counterparts of gamma-ray bursts, and had heard of the Livermore Wide Field of View Camera (even though it had a defense application, it was not classified and some details had been published). He was pleased to discover that Park not only knew about it, but was able to show it to him, "abandoned and unloved ... as they opened the enclosure to see the control electronics, spiders scurried out of sight behind the printed circuit boards". It was clear that this was the right instrument to begin a search for the optical counterparts of gamma-ray bursts, and a collaboration was born. Livermore management was happy to provide funding. Park, her programmers and engineers, and Brian Lee, a University of Michigan graduate student, brought the Wide Field of View Camera back to life as the Gamma-Ray Optical Counterpart Search Experiment (GROCSE).

Unfortunately, GROCSE was not very sensitive. This had not been a problem for its original mission as part of Brilliant Pebbles, for rockets and re-entering warheads are rather bright, but was a serious difficulty in gamma-ray burst astronomy. It could detect a one second flash as faint as 8th or 9th magnitude, but no dimmer. This was perhaps a little better than ETC, but not a great improvement.

GROCSE had the advantage that by responding to BACODINE alerts it was at least sure to be pointing in the right direction. ETC, in the words of its builders, did "not require a trigger from BATSE or any other experiment", a backhanded way of saying it did not take advantage of the information distributed by BACODINE which would have told it where to look to find a burst. They never adopted the strategy of rapid slewing planned for GTOTE and used by GROCSE (and its successors). ETC only gave useful information if the burst happened to be within its pre-determined field of view, which covered about an eighth of the sky. It would be looking the wrong way during seven eighths of the bursts.

Like ETC, GROCSE did not detect any bursts. Their upper limits were sufficient to disprove the naïve assumption that 1% of the burst energy was converted to visible light. However, this assumption was no longer relevant; the binary models which had led to it had been disproved by the BATSE statistical data demonstrating that the bursts must be at cosmological distances. The lower assumption of 0.1% conversion was still permitted by the data.

It was clear that more sensitivity was needed. Sensitivity could be improved in two ways. First, the old Star Wars camera had been designed to produce rapid series of images, not to study faint objects. A new instrument, optimized to do astronomy, would do much better. CCD technology had improved dramatically since the Wide Field of View Camera had been built. The GROCSE CCDs had only 221,184 picture elements each, while state-of-the-art CCDs had 4,194,304, nearly twenty times as many. GROCSE's complicated optical design was also rather "slow", in the terminology of camera and telescope designers, meaning that the lens diameter was comparatively small and therefore did not collect much light[1]. GROCSE also used a complicated system in which light was first passed through fiber optics and then amplified by an inefficient and noisy vacuum tube device called an image intensifier before it reached the CCD.

Second, the BATSE gamma-ray burst coordinates, transmitted through BACODINE, made it possible to reduce the field of view. It was only necessary to look at the patch of sky which might contain the burst, rather than at as much of the sky as possible. By Liouville's theorem, this permitted larger lenses which would collect more light. It, along with the vastly greater number of picture elements on improved CCDs, also meant that each picture element would be smaller, so there would be less starlight and skylight in it to overwhelm the faint hoped-for signal of a gamma-ray burst. An optical system with a field of view (about 16 degrees across) matched to the uncertainties in the BATSE positions could have a sensitivity hundreds of times greater (about 14th magnitude). In essence, BATSE would replace ETC.

[1]The technical term for this is that its f-number, the ratio of focal length to lens diameter, was 2.8, as compared to values between 1.4 and 1.8 for the 35 mm camera lenses used by amateur photographers. ETC originally proposed to use lenses with an f-number of 0.85 but wound up with 1.4. Lenses with smaller f-numbers collect more light and are called "faster" because they permit shorter exposures.

RMT had much too small a field of view to fit the BATSE coordinates, so it would be replaced by a new instrument, initially called GROCSE-II.

New instruments cost money. GROCSE-II would be small, but it would be custom-designed and built, and would advance the state-of-the-art in robotic telescope control and data processing. There were internal funds for work at Livermore, but Akerlof needed support for his work at Michigan. In 1994–1995 he submitted a total of four proposals to the NSF. In each case he received excellent reviews, and a form letter of rejection. GROCSE-II nearly died. Apparently, each dollar of the NSF Astronomy budget had someone's name on it, and there was no room for new people or ideas, even those acknowledged to be original and excellent. He received a little support from NASA, some from an internal University of Michigan research fund, and a crucial grant from the Research Corporation, a private philanthropy not bound by the bureaucratic constraints which hobble the NSF[2].

Scientists are notorious for squabbling about credit for discoveries[3], and sometimes they simply don't get along. The development of GROCSE-II was well underway in early 1996 when an ugly split developed between Akerlof and Park, its two leaders. What may have begun as legitimate differences of opinion soon became a struggle for control. Divorces, in science as well as in marriage, generally involve irreconcilable differences, and usually the parties involved give irreconcilable accounts of what went wrong.

According to Akerlof, Park decided to cut him out of the project, even though it had been his idea to turn the defunct Wide Field of View Camera into the functioning GROCSE instrument. Akerlof and Lee had played a major role in making GROCSE work, as well as in designing GROCSE-II.

[2]The real reasons for NSF funding decisions are hidden behind their form letters. If a disappointed applicant inquires, he will be told of the large number of excellent proposals, but given no insight into how the hard decisions are made. If he suspects favoritism, cronyism, or just closed minds, none can prove him wrong. It appears that the NSF is much more interested in big science than in small science, even though new ideas start small; it may be as hard to get two million dollars as two hundred million, and not much easier to get fifty thousand. The big hogs push the piglets away from the trough. Sometimes they eat the piglets. There is also evidence that the NSF makes decisions for political reasons entirely unrelated to science.

[3]One prominent theorist had the curious habit of sidling up to a younger scientist who had just presented his ideas and saying that he, too, was working on that subject, and that they should write a paper together. The speaker, flattered or perhaps intimidated, would agree, but when the paper was finally written the prominent scientist would have contributed only his name.

Park denied him and the Michigan team access to the GROCSE hardware, software and data. He describes her acts as amounting to "theft of intellectual property", and considered legal action.

Neither Park nor anyone else at Livermore was willing to give her side of the story. Akerlof can be blunt and outspoken. When I telephoned him, his first statement was "I suppose you want me to write your chapter for you.". (I did not and he did not.) This may not make him easy to work with (he withdrew from both the Whipple and the MACHO experiments after some friction), but bland organization men do not make scientific entrepreneurs. On technical matters he is usually right.

Eventually, a settlement was reached. Livermore made a cash payment to the University of Michigan and agreed to support a staff member working on ROTSE. The existing equipment was divided between the two teams, something which Akerlof compared to Solomon dividing the disputed baby. Fortunately, this separation was not fatal, but resulted in two similar but competing experiments. Livermore may have gotten the better end of the settlement, because Park's Livermore Optical Transient Imaging System (LOTIS) was in operation before the end of 1996. Akerlof's ROTSE moved to Los Alamos, again illustrating that the U.S. nuclear weapons laboratories are readier to provide venture capital for new scientific ideas, even those with no connection to weapons, than the government agencies charged with their support. ROTSE was in operation by early 1998.

The GROCSE data, reporting upper limits to the brightnesses of possible optical counterparts to gamma-ray bursts, were published twice, first by Michigan and then by Livermore. Much of the work, especially the data analysis, had been done by Brian Lee. Akerlof was careful to ensure that Lee's name appeared first on the author list (usually a mark that this author bears chief responsibility, and should receive most of the credit, for the work) of the Michigan paper (none of the Livermore people were listed, at their request), but Park's name was first on the Livermore paper (no Michigan people other than Lee were listed)[4]. Quite properly, the BACODINE team were on both author lists. Multiple publication of the same results is usually strongly disapproved of because research papers are supposed to report only *new* results, but was tolerated in this case.

[4]ROTSE papers had the authors listed in alphabetical order, a solution to the problem of squabbling over their order, but one which left the reader wondering if Akerlof was first only because his name begins with the letter A.

The theorists had not been entirely idle, and had tried to make more sensible predictions of the brightness of burst counterparts. The development of relativistic shock models of bursts had led in 1994 to a prediction that at frequencies below the gamma-ray range the brightness (Chapter 14) would vary as the 1/3 power of frequency. Extrapolated down to visible frequencies, it meant that less than a millionth of the energy of a gamma-ray burst would appear in visible light. A bright "burst of the month" would be approximately 18th magnitude. This was very discouraging, because it was far below the sensitivity of ROTSE or LOTIS. Much larger telescopes, with smaller fields of view, would be necessary. The BATSE coordinates would not be accurate enough to point these telescopes, and they would have to wait for future space instruments which could locate gamma-ray bursts more accurately.

Fortunately, the theorists did not stop there. Re'em Sari and Tsvi Piran looked more closely at the physics of the shock produced when a relativistic debris shell collides with the interstellar medium or other dilute gas. There will actually be two shocks, one in each fluid, just as when you clap your hands together both hands sting. If one fluid is much denser (the debris shells may be perhaps a million times denser than the interstellar medium when they collide), the shock in it is much weaker, just as if your hand slapped a boulder rather than your other hand; your hand may be hurt, but the boulder will not be. The shock in the dilute fluid is strong, and makes electrons energetic enough to radiate gamma-rays. The shock in the dense fluid is much weaker. It won't radiate gamma-rays, but it can radiate visible light. The spectrum of the gamma-rays cannot be extrapolated to visible light, because the visible light is produced by a different source with different properties. Sari and Piran predicted that the visible counterparts would be much brighter than simple extrapolation from the gamma-ray burst had implied. Their results depended on many uncertain parameters so that it was impossible for them to be very specific, and the visible to gamma-ray ratio would probably be very different in different bursts. These predictions were presented at a meeting held in Rome in November, 1998, and the paper describing them was distributed electronically to the world-wide astronomical community on January 10, 1999.

By this time LOTIS had been in operation more than two years, and ROTSE nearly a year. Each had received via the GCN (formerly BACODINE) scores of gamma-ray burst positions within seconds of the beginnings of the bursts. If conditions were favorable (night and good weather at the observing site, and the burst above the horizon) the position of the burst was observed. The analysis was slow because the cameras recorded data over the entire large BATSE error circles, which had to be searched for a possible optical transient. It was easier if BeppoSAX or the interplanetary network obtained an accurate burst position. Even though the accurate position only was calculated after some delay, it could be used to guide the search of the LOTIS and ROTSE images obtained during the bursts themselves. The data had to be obtained during the bursts themselves, but there was no hurry doing the analyses.

At first, only upper limits were found. In the best cases these limits, obtained during the bursts themselves, were 13th magnitude or brighter. Data accumulated over several minutes to an hour led to even tighter bounds, as faint as 16th magnitude, but properly these were only bounds on the early afterglow, because the bursts themselves were long since over.

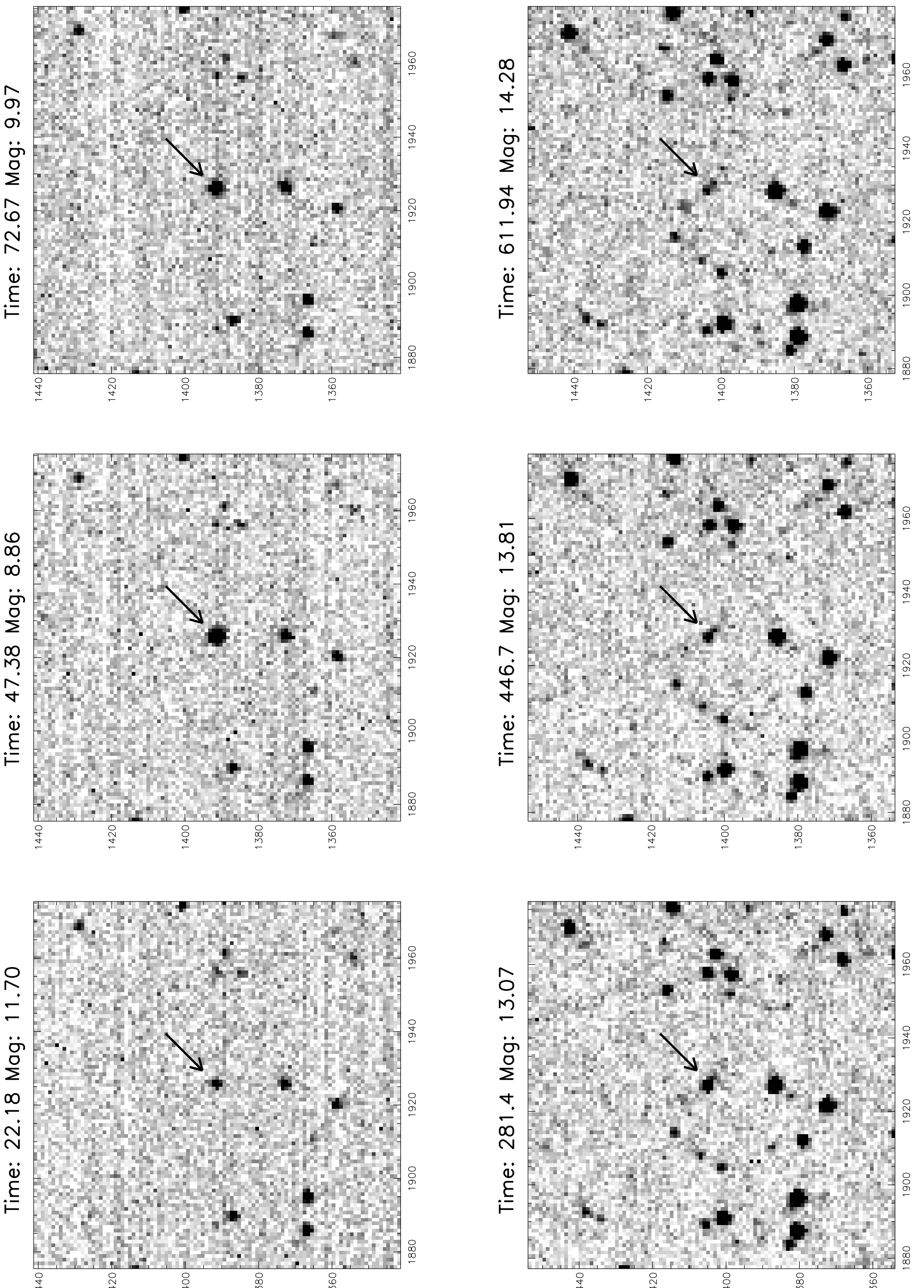
On January 23, 1999, came the breakthrough. BATSE detected a very strong burst, called GRB990123. Within seconds, GCN transmitted its position to astronomers and telescopes all around the world. It was raining at LOTIS, in the hills east of Livermore, but clear at ROTSE in New Mexico; perhaps it was fortunate that Park and Akerlof had split, because there were now two instruments, far enough apart that they had different weather. ROTSE steered to GRB990123 and, for the first time ever, detected a gamma-ray burst with visible light as it was happening. It was unexpectedly bright, 9th magnitude at its peak. The data are shown in Figure 16-1.

Ninth magnitude astounded almost everyone. It was much brighter than the upper limits on other bursts seemed to imply, even allowing for the greater gamma-ray intensity of GRB990123. Naïve extrapolation from the gamma-ray spectrum might have predicted about 16th magnitude (brighter than the 18th magnitude originally estimated because this burst was so unusually intense, and because of uncertainties in the extrapolation procedure itself), but it turned out to be a thousand times brighter still. The prediction made by Sari and Piran a few months before, and published electronically only two weeks earlier, was confirmed. In fact, the conclusion that the ratio of visible light to gamma-rays is higher in some bursts than in others also agrees with their suggestion that the visible brightness depends on several parameters in a complex manner.

Observing a single event of a class is revealing, but it is also tantalizing and frustrating. We do not know how typical GRB990123 was, or how bright the typical gamma-ray burst is—just below the threshold of detection by

LOTIS and ROTSE, or much fainter? These questions will only be answered when the visible counterparts of more bursts are observed. More surprises may be waiting. The holy grail of gamma-ray burst astronomy has been found, and drinking from it will become routine.

Figure 16-1: Visible light images of GRB990123 obtained by ROTSE. The arrow points to its visible counterpart. The times are measured in seconds and counted from the beginning of the gamma-ray burst as recorded by BATSE. The magnitudes are also indicated, with the smallest number (8.86) in the second frame when the visible counterpart of the burst was brightest. This also corresponded to the peak gamma-ray intensity. The upper row of images were five second exposures and the lower row were 75 second exposures, explaining why the background stars appear so much darker (brighter in these negative images) in the lower row. The axis labels are picture elements in the CCD, whose edge occurs at 2048; ROTSE nearly missed this burst, which occurred near picture element 1925 on the horizontal axis! (Reprinted by permission from Nature V. 398 p. 401 ©1999 Macmillan Magazines Ltd.)



Time: 22.18 Mag: 11.70
Time: 47.38 Mag: 8.86
Time: 72.67 Mag: 9.97
Time: 281.4 Mag: 13.07
Time: 446.7 Mag: 13.81
Time: 611.94 Mag: 14.28