RAPTOR Science

Capturing Cosmological "Winks"

by Brian Fishbine

A small robotic observatory system, called RAPTOR, is poised to take movies of fleeting astrophysical events. These movies will help astronomers better understand planetary systems, stars, galaxies, and the universe. Some of RAPTOR's data analysis techniques can also be applied to defense problems.

Researchers Katherine McGowan and James Wren inside RAPTOR-A, one of four robotic observatories in the RAPTOR system. The wide- and narrow-field telescopes mounted on the platform above them can be aimed at any point in the sky in less than 3 seconds. When RAPTOR's computers detect a transient optical event in a wide-field image, they aim the narrow-field telescope at the event to take a close-up movie of it.

On January 23, 1999, a NASA satellite detected a brilliant burst of gamma rays 10 billion light years from Earth. The satellite transmitted the burst's position to a small robotic observatory at Los Alamos National Laboratory called ROTSE, for Robotic Optical Transient Search Experiment. Within 10 seconds, ROTSE pointed its telescopes at the burst and began taking a movie of the most luminous celestial object ever observed. This was also the first time the light from a gamma-ray burst had been recorded as the burst emitted gamma rays. The pulse of light lasted about 80 seconds.

Many distant astrophysical events also produce pulses of light, including exploding stars, extrasolar planets, stellar flares, binary star systems, pulsating stars, and gravitational microlensing events. These "transient optical events" provide important information about the universe. For example, gravitational microlensing studies can help determine the composition of "dark matter," which makes up 96 percent of the universe's mass but emits no light and is therefore invisible. Dark matter in the early universe provided the clumps of mass needed to form galaxies, stars, and planets. (Gravitational microlensing

John Flower

John Flower

The three RAPTOR observatories in the mountains just west of Los Alamos (left to right, RAPTOR-P, -A, and -S). The fourth observatory, RAPTOR-B, is at Los Alamos National Laboratory, 38 miles away. RAPTOR-A and -B are identical; together they provide RAPTOR's stereovision. RAPTOR-S measures the color of a transient optical event. RAPTOR-P searches for planets orbiting other stars and catalogs known celestial objects to help identify transient optical events. The observatories' clamshell lids protect the telescope lenses and other hardware from the elements. The lid for RAPTOR-A is shown open. Weather stations on the observatories provide weather data to the control computers.

occurs when the gravity of a dark massive object passing between Earth and a star focuses the star's light to make it brighter as seen from Earth. Microlensing objects include brown dwarf stars and black holes.)

To capture a transient optical event, however, a telescope must center the event in its field of view before the event disappears. The massive telescopes of conventional observatories move too slowly, but small, computer-controlled telescopes are nimble enough for the task.

Last fall, a new system of robotic observatories became operational at Los Alamos. Called RAPTOR, for Rapid Telescopes for Optical Response, the system took its first movie of a gamma-ray burst in response to a satellite alert on December 11, 2002.

However, RAPTOR can do more than respond to satellite alerts. Equipped with sophisticated computer intelligence, it is the first robotic observatory system that can find and study transient optical events on its own. It is also the only robotic observatory system with stereovision, which allows it to discern between transient optical events and nearby space junk, as well as to detect "killer" asteroids (see the sidebar on page 8).

A New Window on the Universe

RAPTOR could also be the first observatory to take movies of such exotic objects as giant flares on sunlike (solar) stars and orphan gamma-ray bursts. Although these objects are thought to exist, they have been difficult to observe: the few sightings of giant solar flares are in doubt, and orphan bursts have not yet been seen. Only RAPTOR has the intelligence and speed to identify and capture these fleeting events.

And there are good reasons to study such events. A giant flare on the sun could destroy Earth's climate and its inhabitants. Even an ordinary "small" flare can affect the weather, overload power grids, and knock out satellites. Studies of giant flares on other solar stars could help astronomers predict the likelihood of such a flare on our sun.

Orphan gamma-ray bursts are of interest because at least some gamma-ray bursts are caused by exploding stars, which seed the universe with the heavy elements of which planets—and people—are made. Studies of gamma-ray bursts will elucidate how stars explode (see the sidebar on gamma-ray bursts on page 10).

System Overview

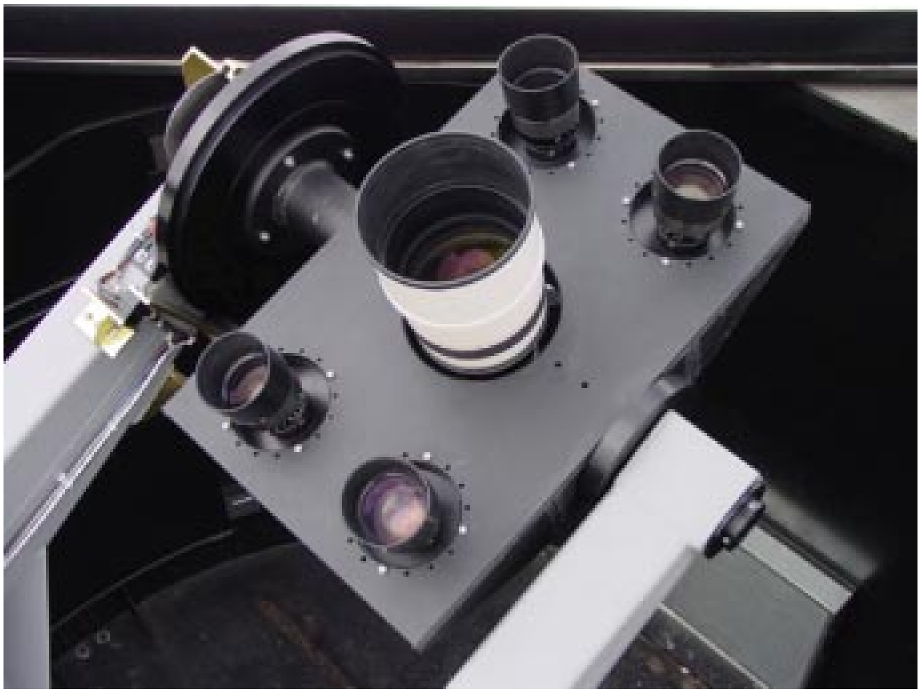
RAPTOR was built by a Los Alamos team headed by astrophysicist Tom Vestrand; the project was funded by the Los Alamos Laboratory Directed Research and Development Program. The system consists of four small robotic observatories. RAPTOR-A, -S, and -P are at Fenton Hill, in the Jemez Mountains west of Los Alamos. RAPTOR-B is at the Los Alamos Neutron Science Center, 38 miles away. Computers located between the two sites analyze data from the observatories and send commands to computers at the sites that control the observatories' telescopes and digital cameras. The computers communicate through the Internet.

RAPTOR-A and -B are identical and together provide RAPTOR's stereovision. Each observatory consists of a wide-field telescope and a narrow-field telescope mounted on a platform that can swivel to any point in the sky in less than 3 seconds. The telescope platform is the fastest ever built.

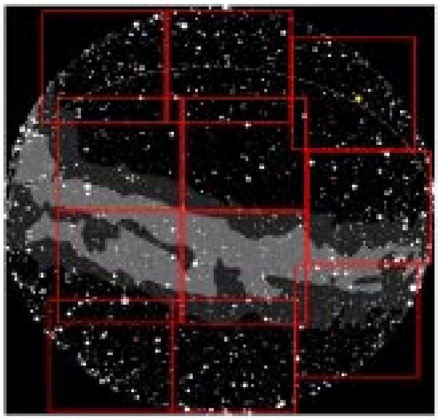
With a field of view of 38 by 38 degrees, each wide-field telescope can cover the sky in eleven patches. However, RAPTOR usually focuses on about four patches near the zenith, where it is easier to measure the brightnesses of celestial objects. Several factors complicate measurements near the horizon: the sky background is brighter because of the sun and nearby towns, celestial objects are dimmer because their light passes through more air to reach the telescopes, and the amount of air the light passes through changes rapidly with the elevation angle.

Usually, RAPTOR monitors one patch of sky for several hours and then moves to another patch. While monitoring, RAPTOR takes two consecutive 30-second exposures through its A and B wide-field

The four 85-millimeter telephoto lenses that make up RAPTOR-A's wide-field telescope surround the 400-millimeter telephoto lens of its central narrow-field telescope.



Tom Vestrand



The patches of sky that the wide-field telescopes usually cover during RAPTOR's nightly searches for transient optical events.

telescopes and analyzes the resulting digital images. If it sees an interesting event, RAPTOR zooms in for a closer look with the two narrow-field telescopes. The system also trains RAPTOR-S on the event to measure how the light intensity changes with wavelength. (RAPTOR-P, a very recent addition, looks for the slight dip in light intensity that can be seen from Earth when an extrasolar planet crosses its parent star's bright disk. This effect was used by a group at Princeton University to discover an extrasolar planet in 2001. RAPTOR-P also catalogs known celestial objects to help the system identify transient optical events.)

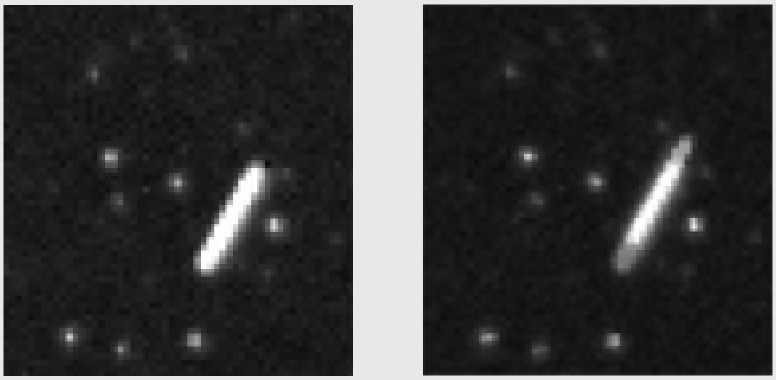
RAPTOR mimics human vision in its searches. If its computer brain detects something interesting in its wide-field "peripheral" vision, it quickly swivels its "eyes" to focus on the action. Then, like the cones in the fovea of the human eye, densely packed light sensors in RAPTOR's narrow-field central vision sharply image the region of interest. RAPTOR also uses two "eyes" for its stereovision.

Detecting "Killer" Asteroids

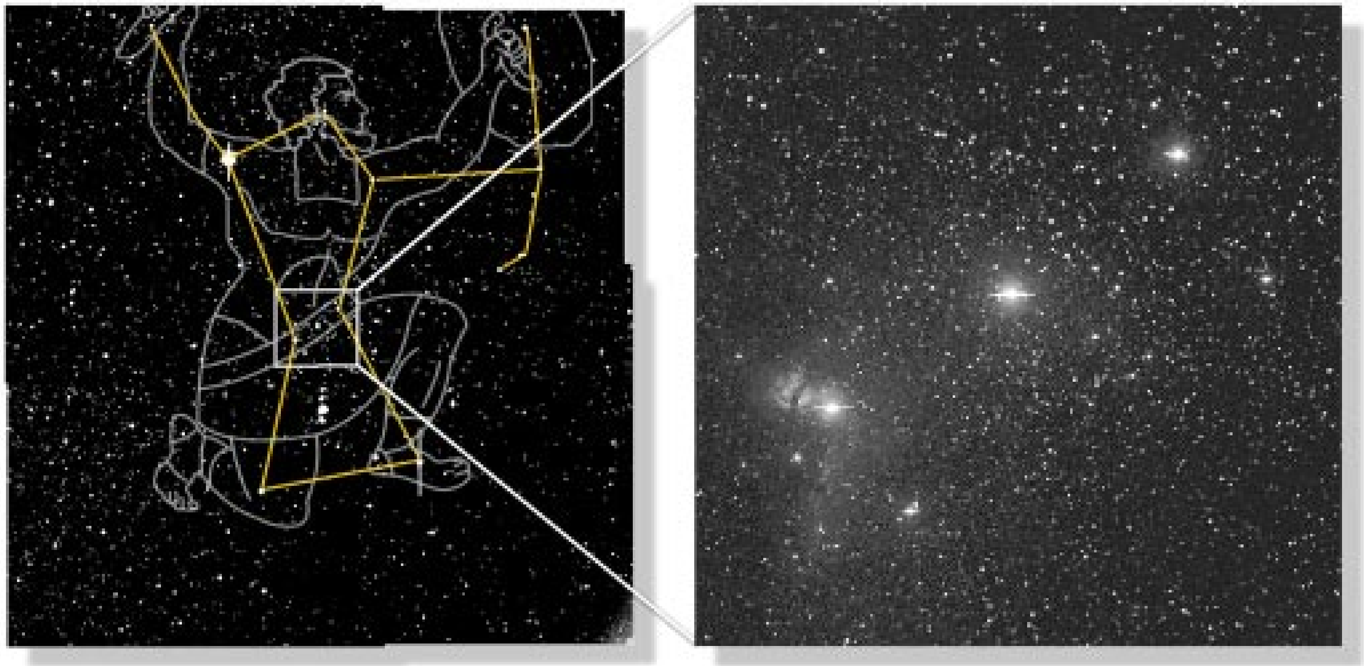
In addition to being able to find transient optical events, RAPTOR can detect "killer" asteroids, like the one that probably wiped out the dinosaurs 65 million years ago. RAPTOR's stereovision permits parallax measurements that can detect such asteroids as far away as the moon. Measuring an asteroid's parallax has an advantage over the current detection method, which looks for the streak an asteroid leaves in a time exposure of the night sky. An asteroid that leaves a streak has a component of motion perpendicular to a straight line drawn from Earth to the asteroid. But the asteroids of most concern are headed straight for Earth and thus leave no streaks. Fortunately, a parallax measurement can easily detect such objects.

Early last year, astronomers calculated that an asteroid would come within 100,000 kilometers of Earth later in the year. Using information provided by the astronomers, RAPTOR took the first-ever stereo views of an asteroid (see photos below). The asteroid's parallax is obvious, as is its streak—which proved the asteroid would miss Earth.

Although a killer asteroid detected as far away as the moon would strike Earth in 8 hours, such advanced warning would give some time to start evacuating people from the coasts, where the impact-induced tsunami would pose the greatest threat to populated areas. (Since three-fourths of Earth's surface is covered by ocean, an ocean impact is the most likely scenario.) Replacing RAPTOR's current telescopes with an array of 1-meter telescopes, however, would enable RAPTOR to provide advanced warning of a week or more.



RAPTOR's stereo view of last year's near-Earth "killer" asteroid.



At each of the RAPTOR-A and -B observatories, four 85-millimeter telephoto lenses provide four digital images that are stitched together to form a 38- by 38-degree wide-field image. On the left is a RAPTOR-A wide-field image of the Orion constellation. At the upper left, the reference star marked by a vertical line is Betelgeuse. The reference star at the lower right (in Orion's foot) is Rigel. To search for a transient optical event, RAPTOR's computers measure the positions and brightnesses of up to 250,000 objects in each wide-field image and compare their positions and brightnesses to those of known celestial objects—all in 10 seconds or less. If the computers find an object that appears to be a transient optical event, RAPTOR zooms in with its narrow-field lenses to take movies of the object. On the right is a 4- by 4-degree narrow-field image taken by RAPTOR-A's 400-millimeter telephoto lens. The three brightest reference stars marked by horizontal lines are the main stars in Orion's belt.

Sky Monitoring

Weather permitting, RAPTOR-A and -B measure the positions and brightnesses of several million stars each night. On a moonless night, their wide-field telescopes can detect objects as faint as the 13th magnitude. (By comparison, the faintest objects visible to the unaided eye—6th magnitude—are 300 times brighter.) Each narrow-field telescope has a field of view of 4 by 4 degrees and can detect objects as faint as the 17th magnitude.

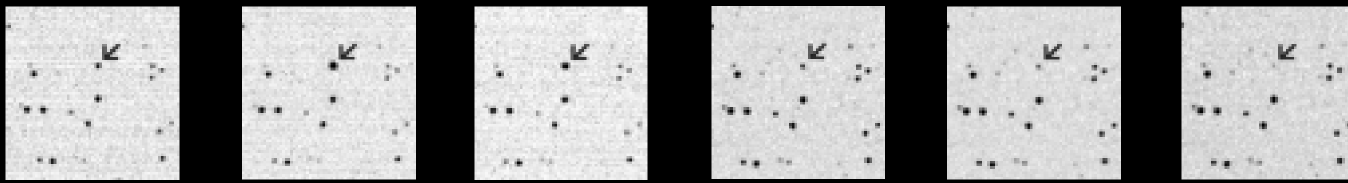
Although RAPTOR is expected to find many transient optical events on its own or by responding to satellite alerts, the data collected through sky monitoring are valuable on their own. For example, by examining the data archives produced during ROTSE's sky monitoring, scientists were able to study the visible light accompanying a brief x-ray event months after a satellite detected it.

To Zoom or Not to Zoom?

To capture a transient optical event, RAPTOR must "think" and act fast. The system has one minute to decide if any one of up to 250,000 objects in a wide-field image is a transient optical event. In contrast, other robotic observatory systems capture transient optical events by chance or by responding to satellite alerts or to commands from humans, who are much slower and less precise than RAPTOR.

To detect a new object in a wide-field image, RAPTOR compares the position and brightness of each object in the image with those of known objects identified in previous scans. (Maintaining the list of known objects is itself a considerable computer task.) To make comparisons, RAPTOR first corrects for changes in the objects' apparent positions caused by optical aberrations in the telescope lenses and for changes in the objects' apparent brightnesses caused by atmospheric attenuation and lens vignetting (the loss of light near the edge of a lens). RAPTOR makes these corrections for all the objects in a wide-field image in 10 seconds or less.

When RAPTOR finds a new object in the first of the two consecutive images provided by both its A and B observatories, it determines if the object



22 s M=11.7 | 47 s M=8.9 | 73 s M=10.0 | 281 s M=13.1 | 447 s M=13.8 | 612 s M=14.3

Mysterious Gamma-Ray Bursts

Gamma-ray bursts were discovered in signals from satellites designed and built at Los Alamos. The satellites' mission was to verify compliance with the nuclear test ban treaty by looking for the x-rays and gamma rays produced by a nuclear explosion in space. Los Alamos scientists published their discovery of gamma-ray bursts in 1973, concluding that the sources of the bursts were cosmic and not terrestrial or solar. The scientists also tried—but failed—to relate the bursts to supernovas.

Burst gamma rays are photons with energies of ten thousand to several million electronvolts. Because of their energies, these gamma rays are highly attenuated by the atmosphere and thus can be detected only in space. (In contrast, the photons of light emitted by some bursts have energies of about 1 electronvolt and pass easily through the atmosphere. These photons can be detected by ground-based instruments such as the RAPTOR observatories.)

Modern satellites detect about one gamma-ray burst a day. A burst can last from a few thousandths of a second to more than 15 minutes. The closest burst, detected on March 29, 2003, was 2 billion light years from Earth, but 10 billion light years is more typical. Such large distances mean the bursts have occurred at the "edge" of the universe, or when it was much younger. For example, the light from a burst 10 billion light years away—which has taken 10 billion years to reach Earth—occurred when the universe was 30 percent of its present age. Gamma-ray bursts thus provide a window on the early universe.

For a time, the bursts' enormous energies puzzled astrophysicists. For example, the gamma-ray burst captured on January 23, 1999, by ROTSE, a robotic predecessor of RAPTOR, was the most luminous celestial object ever observed. (Although the observed brightness of an object decreases as its distance from the observer increases, its *intrinsic* brightness, or luminosity, is independent of the distance.) Assuming the burst emitted radiation uniformly in all directions, astrophysicists estimated its energy to be about 10^{32} megatons, or the energy of two solar masses. (Einstein's equation, $E = mc^2$, equates energy E and mass m, where c is the speed of light.)

However, light measurements of the 1999 burst made more than three days after it occurred supported the idea that the gamma rays and the light were in fact emitted in collinear beams that just happened to shine on Earth, like a searchlight. For a beam scenario, the estimated burst energy was more reasonable—about 10^{29} megatons, the energy of a typical supernova explosion.

Astrophysicists now believe that a burst's gamma rays are emitted in a tight beam and that its light is emitted more broadly. Thus, if Earth is slightly off the beams' axis, the light flash would be seen on Earth but the gamma-ray burst would not. Such bursts are called orphan gamma-ray bursts. Although orphan bursts have never been observed, astronomers believe they exist, and RAPTOR is expected to find many of them. When it does, astronomers will be able to compare the rates at which orphan bursts and ordinary bursts occur to determine the average width of the gamma-ray beam. This information will shed light on how the bursts are produced.

ROTSE measurements also showed that the light from the 1999 burst faded rapidly in the first 10 minutes, as shown above in the six-frame movie. (These first-ever measurements of a burst's early light were possible only because ROTSE's telescopes were pointed at the event within seconds of the satellite alert.) The magnitude data cast doubt on a generally accepted theory that the shock wave generated by a supernova interacts with the gas surrounding the explosion to produce both light and gamma rays. Instead, the ROTSE data suggested that the gamma rays are produced closer to the explosion.

Although there had long been hints that gamma-ray bursts and supernovas were connected, there had been no proof of that connection until the "nearby" burst of March 29, 2003. Because the burst was so close and bright (astronomers joked about it casting shadows), scientists were able to measure its light in detail for several weeks. About a week after the burst, the spectral signature of a supernova appeared in the burst's fading afterglow, which proved that gamma-ray bursts and supernovas can be intimately connected. In fact, it is now clear that at least some gamma-ray bursts are produced by supernovas.

appears in the second images as well. This procedure eliminates artifacts produced, for example, by a cosmic ray passing through a light-sensor element in one of the digital cameras. False positives are a major problem for robotic observatories.

If an object passes this first test, RAPTOR measures the object's parallax to determine if the object is truly distant or merely an airplane, a meteor, a satellite, or a piece of space junk orbiting Earth. To qualify as a transient optical event, the object must be at least as far away as the moon.

RAPTOR measures parallax by comparing the two images from its A and B observatories. The positions of distant objects are the same in the two images, but the positions of close objects are different. This difference is the parallax. As with human vision, the closer the object, the greater the parallax. Stereo comparison also identifies malfunctioning light-sensor elements in the digital cameras, which can also mimic transient optical events.

No Shortage of Brains

To perform its complex tasks quickly, RAPTOR uses sophisticated software residing on nearly twenty personal and server computers. RAPTOR has far more computer intelligence than any other robotic observatory system.

Each telescope platform is controlled by its own personal computer. Also, a dedicated computer transfers the images from each digital camera to the system, which takes about 5 seconds per image. Because a computer is assigned to each camera, the transfers occur in parallel to reduce the total image-transfer time. For example, the total transfer time for a wide-field image, which consists of four slightly overlapping smaller images stitched together, is also about 5 seconds. The computers assigned to the cameras also measure the celestial objects' positions and brightnesses.

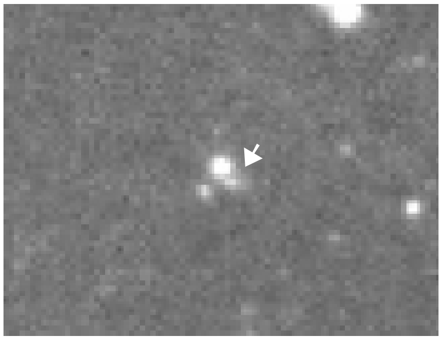
An image-server computer at each site analyzes data from the site's digital cameras and their computers for possible transient optical events. The image server then sends a list of candidate events to an alert-server computer located between the two sites. The alert server compares the lists from RAPTOR-A and -B observatories and identifies new objects that have no measurable parallax.

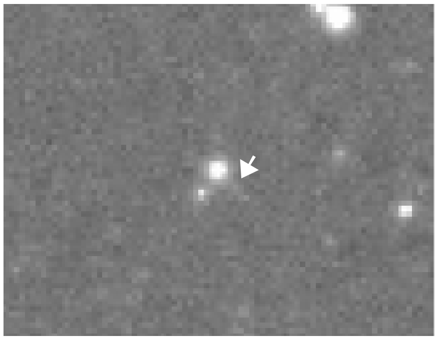
RAPTOR's master control consists of three computer programs that control the computers that in turn control the telescope platforms and the digital cameras. On the basis of data it receives from weather stations at each site, one of these programs also controls the observatories' domes. The programs also reside on a computer located between the two observatory sites.

Finding a Needle in a Haystack

RAPTOR's sky-monitoring data archives will provide valuable information. They offer a nearly continuous record of the light emitted by a large fraction of the celestial objects visible from Earth with a brightness of at least the 13th magnitude. Each week, sky monitoring adds up to 1 terabyte (1,000 gigabytes) to the data archives, which can be mined for interesting astronomical objects.

For example, a team of scientists from Los Alamos and the University of





RAPTOR captured its first transient optical event on December 11, 2002. The upper photo shows the light emitted by a gamma-ray burst 64.9 seconds after a satellite detected the burst. In the lower photo, taken 9 minutes after the burst was detected, the object is nearly invisible. These images were taken by RAPTOR-B. (RAPTOR-A was not yet operational.) They proved that even a gamma-ray burst with weak gamma-ray emission (as measured by the satellite that detected the burst) can generate a bright burst of light.

The first of thirty frames in a movie of the 1999 Leonid meteor shower taken by ROTSE, a robotic predecessor of RAPTOR. This frame shows the cloud produced when a meteor exploded at an altitude of about 85 kilometers just northwest of Las Vegas, New Mexico.

Michigan has used a computer program to identify 1,781 variable stars in the ROTSE data archives. (Variable stars help astronomers measure distances to other galaxies and study the galaxies' evolution.) About 90 percent of the variable stars had not been identified before. The computer program found the variable stars using the same process human astronomers follow. However, a team headed by Los Alamos astrophysicist Przemyslaw Wozniak has also programmed a computer to devise its own ways to find patterns in the ROTSE data. This method could discover entirely new types of stars.

Wozniak's "machine-learning" technique resembles those used by credit card companies to detect fraud from anomalous spending patterns. (In fact, Los Alamos scientists developed some of the machine-learning techniques currently used by MasterCard to detect fraud.) In both cases, the techniques look for a few interesting patterns or events hidden in huge masses of data. In essence, they are looking for a needle in a haystack.

Defense scientists are also interested in finding "needles." They want to distinguish between the warheads and the decoys deployed by a hostile intercontinental ballistic missile, a scenario that includes many fast-moving objects with varying light intensities against a backdrop of stars. Defense scientists also want to detect the unique electromagnetic signature of a missile launch within a "forest" of signals whose sources range from cell phones to the sun. The techniques developed to help RAPTOR find needles in the cosmic haystack could help solve these problems as well. ■

The Researcher

John Flower

Tom Vestrand has a Ph.D. in astrophysics from the University of Maryland. His primary interests are high-energy astrophysics and the physics of rapid astrophysical transients. Before joining Los Alamos in 1999, he was a faculty member at the University of New Hampshire for 10 years and the principal investigator for the Gamma-Ray Spectrometer Experiment on NASA's Solar Maximum Mission Satellite. He was also involved in several other spacecraft missions.