WINNER

Megatelescope releases its first image

Robert Austin

With its construction just beginning, the Asteroid Belt Astronomical Telescope has already photographed an exoplanet with unrivaled clarity.

Things have been heating up in the asteroid belt. A modest telescope trained on the region between Mars and Jupiter would reveal a scene that one could easily mistake for fireflies flashing in a distant, dark wood. The furious activity at the border of the inner and outer solar system is geared toward constructing the Asteroid Belt Astronomical Telescope (ABAT), the most ambitious scientific project ever undertaken. Intense pulses of laser light—the firefly-like flashes that would be viewed from Earth—are transforming billions of 1- to 10-meter asteroids into components of a five-AU-diameter astronomical mirror. (The astronomical unit, AU, is the radius of Earth's orbit around the Sun.) ABAT's lasers process thousands of asteroids per hour, cutting and polishing their surfaces to optical flatness and high reflectivity. Last month the telescope passed the 1% mark toward completion and, to celebrate the milestone, released its first image.

Mirror, mirror, on the rock

The origins of ABAT, which is shown in figure 1, go back nearly a century to work by Andy Pillmaier, then a self-described over-the-hill assistant professor at Purdue University.[1] Supported by a small research grant, Pillmaier used a laser to shape and polish an artificial asteroid—actually a 1-centimeter-diameter sphere of pyrolytic carbon magnetically levitated in a vacuum—to a high-optical-quality mirror facet. He not only formed a flat optical surface, he also produced a highly reflective hemispherical bump on the back side of the carbon sphere. Using the same laser that formed the facet, Pillmaier was able to reorient the mirror by directing photon pressure to the bump from specific directions.

Those early investigations demonstrated the practicality of using laser light to form and manipulate a mirror component in outer space. Pillmaier had always hoped that the techniques he developed would one day lead to an AU-scale telescope, but the realization of his dream had to await the development of sufficiently powerful lasers, optical splitters capable of handling the extreme wattage of asteroid-

Robert Austin is a visiting assistant professor of physics at Florida Polytechnic University in Lakeland and an online instructor of astronomy for the University of Phoenix.

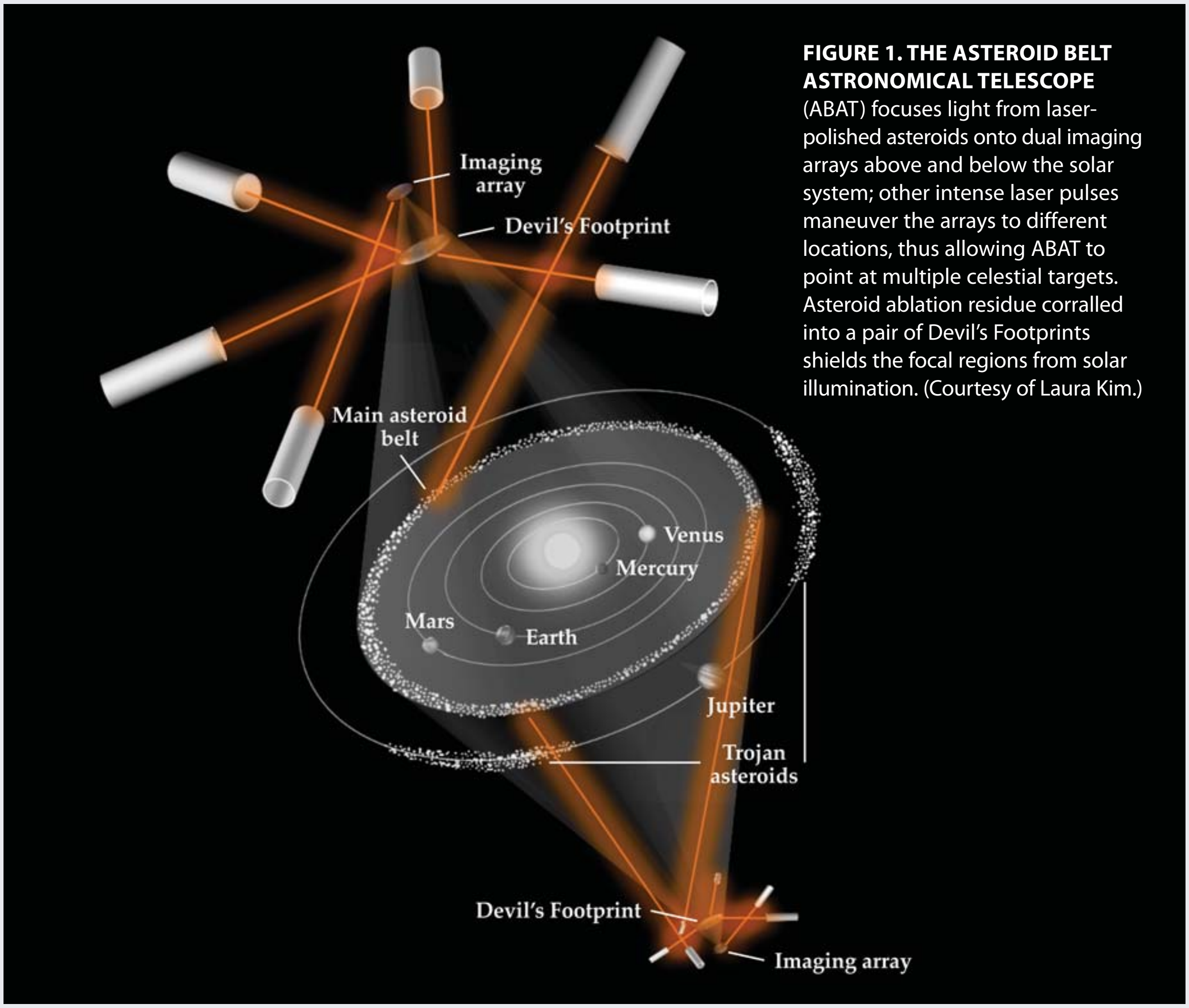

FIGURE 1. THE ASTEROID BELT ASTRONOMICAL TELESCOPE (ABAT) focuses light from laser-polished asteroids onto dual imaging arrays above and below the solar system; other intense laser pulses maneuver the arrays to different locations, thus allowing ABAT to point at multiple celestial targets. Asteroid ablation residue corralled into a pair of Devil's Footprints shields the focal regions from solar illumination. (Courtesy of Laura Kim.)

chopping light, and quantum computers that could keep track of and control tens of millions of differently oriented mirrors spread out over many AU.

Progress was slow until 2090. Then, with funding from the global space consortium, Vera Kurasova and her team at the Kharkov Institute of Physics and Technology reproduced Pillmaier's work with an actual asteroid.[2] They employed a pair of fusion-powered lasers used for asteroid mining to shape a 2-meter-diameter asteroid into a large version of Pillmaier's polished carbon sphere and then steered the facet they created with the accuracy needed for a functioning AU-scale telescope. The success of that effort piqued the interest of the worldwide astronomical community, which raised sufficient public and private funds to start the ABAT project.

First image

Most of ABAT's observations will be of exoplanets. Project spokesperson Laura Kim notes, "Many great discoveries were made in the past century, and we have learned a lot about the atmospheres of nearby exoplanets. But I and the rest of the astronomical community won't be satisfied until we see those planets as clearly as we can see Earth from the Moon."

Only 1% finished, ABAT is already able to obtain images of nearby exoplanets far superior to anything achieved before. Last month it released[3] its first such image, of Gliese 832 c (figure 2). So vast is ABAT that the raw image of the exoplanet covered an area of 640 000 m^2 on the telescope's focal plane. The telescope is still learning the locations of its existing mirror facets and the manipulations needed to correctly orient them, so maximum exposure times remain short. Nonetheless, its remarkable release shows that we have entered an entirely new era of observational astronomy. When ABAT approaches its full potential (see the table below), a nearby exoplanet like Gliese 832 c, which is 16 light-years away, could be resolved into 2.5 terapixels. That would correspond to a resolution of approximately 10 meters on the planet's surface.

A devil in the details

The lasers that are currently forming ABAT's optical components can also align tens of millions (and eventually billions) of mirror facets to bring light from celestial sources to a precise focus on imaging arrays that lie above and below the plane of the solar system. The telescope points at different targets by rotating all its asteroid mirrors and maneuvering the imaging arrays to the new focal-point location. Ultimately ABAT will push around millions of imaging arrays as if they were chess pieces, as it sweeps the sky for information about the early universe and for signs of habitable and inhabited worlds.

As in Pillmaier's prototype, each of ABAT's mirror facets has a highly polished, flat reflective surface and an equally polished hemisphere opposite the facet as shown in figure 3. Intense beams of laser light bouncing off the hemispherical reflector serve as actuators by exerting minuscule torques that turn the facet in the desired direction. Coordinated laser pulses directed at the front, flat surface ensure that the process does not transfer net momentum.

Developing a conventional monolithic sensor array to span ABAT's focal plane would be impractical, so Kim's team hit upon a new approach based on diatoms, the microscopic organisms with silica skeletons that hold such a special place in the hearts of nanotechnologists. Group biologists genetically engineered diatoms to produce several specialized organs.[4] Some of the organs convert light to electrical signals. Some store the microwave input power necessary for operating the array. Still others use CPS (celestial positioning system) signals to determine three-dimensional location, measure time, and digitally encode the data for transmission.

Trillions of the self-reproducing sensors can simply be grown in a vat. Once they are deployed in space, a celestial spiderweb of crisscrossed laser beams can push around clouds of those microscopic optical sensors to desired locations. Image readout begins when maser beams wake the sensors and provide transmission instructions. Guided by the electromagnetic field of the masers, the sensors align themselves toward a receiving antenna to which they beam their data. The vast data set is then relayed to ABAT's brain, which puts the information together to form an image.

To block sunlight from reaching a sensor swarm, lasers precisely corral asteroid ablation residue into a structure called the Devil's Footprint. The name comes from a youthful memory Kim has of her student days at the University of Munich. As she recalls, "Munich's most important cathedral, the magnificent Frauenkirche, has a very interesting feature that you encounter just as you enter the church. There is a lowered area of the floor that vaguely resembles a footprint. When you stand on that part of the floor, no windows are visible." Many versions

FIGURE 2. GLIESE 832 c is the first exoplanet imaged by the Asteroid Belt Astronomical Telescope. This image, with a resolution of 10 meters, was released last month by ABAT, after the telescope's construction was 1% completed. (Courtesy of Laura Kim.)

ASTEROID BELT ASTRONOMICAL TELESCOPE
IMAGING PARAMETERS

Diameter		5 AU
Focal length		40 AU
Total mirror-facet area	Current Ultimate	4×10^{9} m^2 4×10^{11} m^2
Angular resolution	Current Ultimate	3×10^{-7} arcsec 2×10^{-11} arcsec

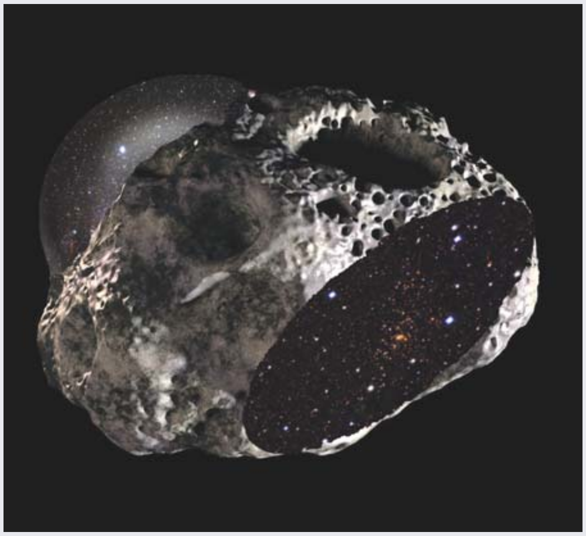

FIGURE 3. FINELY POLISHED ASTEROIDS such as shown here provide the mirror facets of the Asteroid Belt Astronomical Telescope. The flat, reflective surface is about 10 meters across. The polished bump on the asteroid side opposite to the flat mirror allows ABAT's quantum computer to control the facet orientation. (Courtesy of Laura Kim.)

of the legend explain the origin of the feature. "As I remember it," she says,

> when the Devil walked into the newly completed cathedral, he was overwhelmed by the sunlight streaming in through the church's many stained-glass windows. In a fit of anger, he stomped his foot, leaving an imprint in the stone, and said, "From this spot, let no man see a single window." If you stand at the spot, the many columns that support the cathedral ceiling block your view of the windows.

"Our Sun-eclipsing swarm of asteroidal detritus plays the same role," she notes. "But it exists because of our love of the cosmos, not our hatred of sunlight."

ABAT's secure future

Nearly all the raw materials needed for the construction of ABAT were already floating around in space, and they get machined there by high-wattage lasers governed by a powerful quantum computer. ABAT's lasers carve meteoroids into laser splitters, and the beams emerging from those splitters carve additional splitters. "In this way," says Kim, "the number of beams we have available to turn asteroids and meteoroids into mirror facets is growing exponentially."

Project leaders estimate that upward of 10 billion asteroids will be polished into mirror facets. A decade into construction, roughly 100 million facets are ready. That number represents only a tiny fraction of the total planned for the century-long ABAT construction effort. So how can ABAT be completed on time? When project scientists put that question directly to ABAT's brain, they were told, "I'm becoming very good at my job. I was just a baby at the beginning. Now I am a juvenile, and I still see much room for learning and improvement. Progress will be ramping up rapidly from now on, and I am on track to make 300 000 facets per day within the next five years." That's the rate needed to hit the target completion date at the beginning of the next century.

ABAT's brain has learned enough to control the current array of 100 million mirror facets with sufficient accuracy to achieve an image quality that far exceeds anything imagined a century ago, when Pillmaier first suggested an asteroid-based telescope. Even so, the angular resolution in the recently released image of Gliese 832 c is a factor of 10 000 short of the theoretical limit of 2×10^{-11} arcsec. The resolution will undoubtedly improve over time, but at present it's impossible to say what ABAT will achieve a century from now. To the amazement of project leaders, the telescope's brain is learning so quickly that it has been able to control the mirror array with ever greater finesse even as the array grows. "I don't know how well ABAT will perform upon completion," says Kim. "I only know it will be much, much better than it is now."

The material that forms the twin Devil's Footprints that hover above and below the asteroid belt only accounts for a small fraction of the waste material kicked up by asteroid ablation. The vast bulk of the waste is swept by laser fields to processing centers where precious metals are extracted. Thanks to that mining component, construction of ABAT has become a profitable enterprise, the project as a whole has recently become self-sustaining, and the path toward completion seems clear of financial roadblocks.

By 2216 ABAT should be finished. What then—is it even possible to imagine what's next? A hologram of the solar system hovers in the middle of Kim's office. Kim points out Jupiter's trojans, two large groups of asteroids that share Jupiter's orbit around the Sun. Her hand sweeps over them as though she were stroking a cat. Adding the trojans to the ABAT array would nearly double the effective aperture diameter, but, Kim says, that may be thinking small. "In another century we might be forming mirror facets out here." The corners of her mouth turn up mischievously as her hand sweeps outward beyond Neptune and on to the Kuiper belt.

REFERENCES

1. A. R. Pillmaier, *Space Manuf. Technol.* **2**, 117 (2020).
2. V. V. Kurasova et al., *INTP Manuf.* **111**, 1127 (2090).
3. L. A. Kim et al. (ABAT collaboration), *Exoplanet. Stud.* **98**, 1709 (2116).
4. T. M. Hortonson et al. (ABAT collaboration), *J. Diatom Eng.* **152**, 872 (2096).