Searching the Universe for Exotic Explosions

ECE professors Steve Ellingson (right, standing) and Cameron Patterson (seated) have teamed with physicist John Simonetti (left) to search the heavens for exotic events.

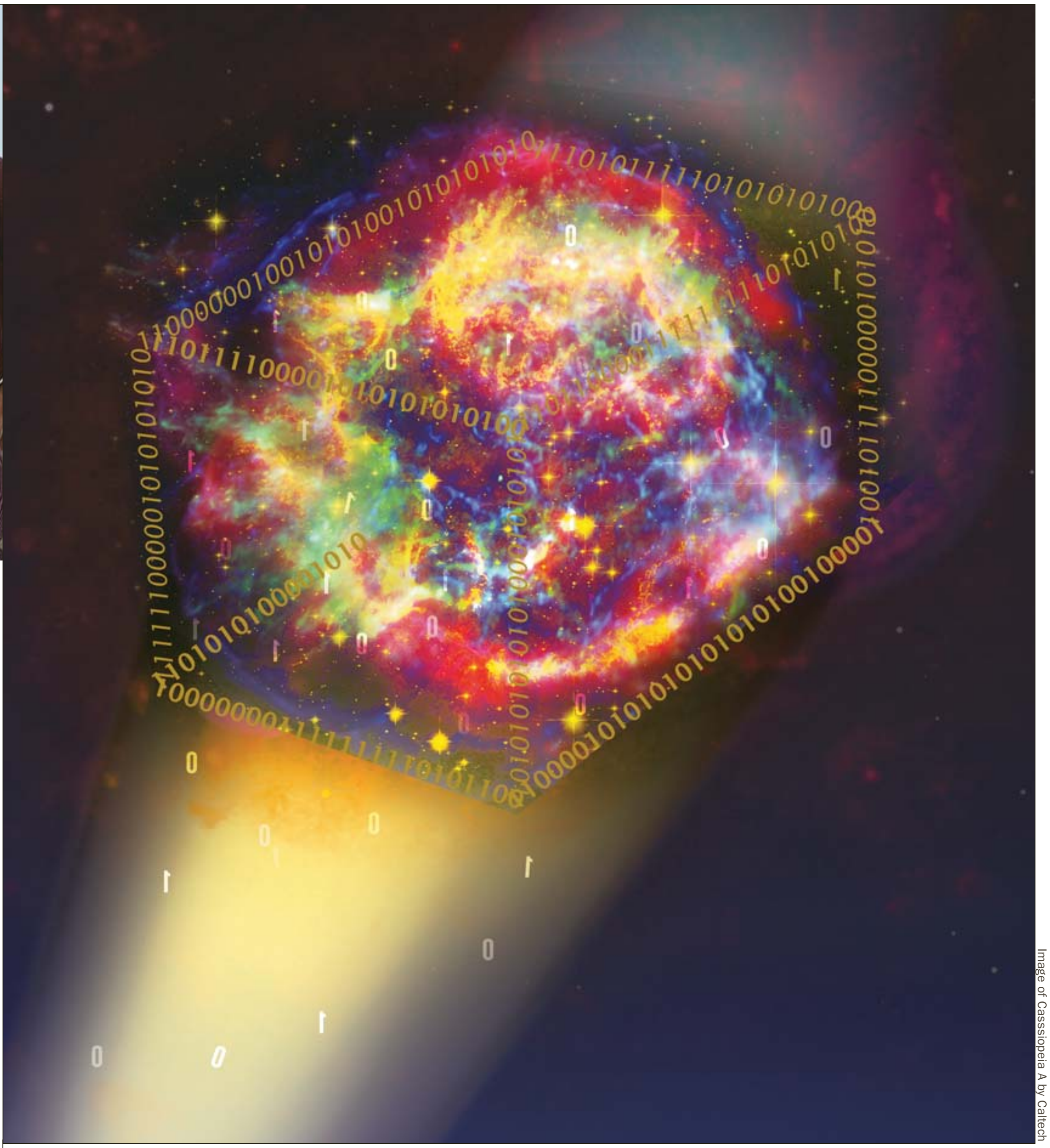


Image of Cassiopeia A by Caltech

Using aluminum pipes, low-cost equipment, and a unique, reconfigurable computing system, ECE and physics researchers have created a radio telescope to search the skies for "exotic physics" phenomena that exist in theory, but are not yet discovered. Beginning this summer, the telescope will begin its continual listening for the tell-tale radio frequency signature of transient astrophysical events such as exploding primordial black holes, gamma-ray bursts, supernovae, and more.

Called the ETA, for Eight-meter-wavelength Transient Array, the instrument represents a new breed of telescope that uses low-cost, simple antennas and receivers while taking advantage of high-performance, real-time digital signal processing and reconfigurable computing for analysis. The project is funded by a $447,000 grant from the National Science Foundation (NSF).

The telescope was designed to conduct a continuous search of the radio sky for single, dispersed radio pulses associated with the explosions of a broad class of astronomical objects called transients. Many of these transients are believed to be associated with rare astronomical events that are postulated, but not yet detected, including coalescing neutron stars and exploding primordial black holes.

“We tend to think of astronomical events unfolding over very long time scales,” said John Simonetti, associate professor of physics and the project scientist. “So, discovery of astronomical events occurring over shorter timeframes tends to be a surprise,” he said, referring to the unexpected discoveries of periodic emissions from neutron starts (pulsars), aperiodic “giant pulses” from pulsars, and gamma ray bursts.

“It is reasonable to expect continued detection of new sources at low radio frequencies — but only if we look,” he said.

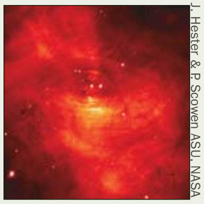
“The transient sky is mostly unexplored, since existing instruments are terrible for this,” said Steve Ellingson, assistant professor of ECE, and principal investigator on the project. “Existing ‘big dish’ telescopes have to be pointed, and have very narrow field-of-view — like looking at the universe through a soda straw,” he explained. “ETA can see the whole sky all the time, and that’s a huge advantage if you are looking for rare single pulses. We would like to know what is going on in the 99.999 percent of the radio sky we aren’t currently observing.”

Almost belying its galactic promise, ETA is a visual surprise: it looks like 12 pipes stuck in the grass at the

Astronomical Explosions
What is ETA looking for?

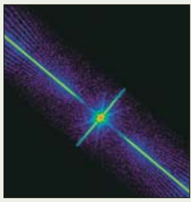
ETA is a radio telescope designed to observe the short dispersed radio pulse — the radio transient — that is expected to be produced by a number of high-energy astrophysical phenomena. The ETA will search for these transients during continuous observation of almost the entire northern hemisphere of the sky.

Giant Pulses - The Crab Pulsar


J. Hester & P. Scowen ASU, NASA

A pulsar is a pulsating radio source, with a typical period of less than one second. It is well accepted that pulsars are rotating neutron stars and that the pulse period equals the rotation period of the star. A handful of pulsars are known to emit an occasional “giant” or “nano-giant” pulses, such as the Crab Pulsar. At radio wavelengths, only the Sun appears brighter than the Crab pulsar during one of these nano-giant pulses. ETA is expected to detect the Crab’s giant pulses, providing a useful diagnostic for the system.

Exploding Primordial Black Holes


NASA Cfa/J. McClintock et al

Primordial black holes may be produced as a by-product of the density fluctuations in the Big Bang. There may be as many as 10^{23} of these black holes in our Galaxy alone.

Some combinations of general relativity and quantum mechanics suggest that black holes evaporate. The evaporation process quickens as the mass of the black hole decreases and the process ends in an explosion releasing 10^{30} erg or more of energy in less than one second. The resulting relativistic expansion of charged particles could interact with the interstellar magnetic field to create an electromagnetic pulse that could be detected in the low-frequency radio spectrum.

Gamma-Ray Bursts

Gamma-ray bursts are short, intense bursts of gamma radiation coming from a localized, random direction. These short duration events are undoubtedly due to high-energy events, which, in fact, are radiating in all wavelengths. Fading optical emission and even radio emission has been observed from such events, but the prompt radio emission would be very useful in pinning down the physics of the bursts, the nature of object, and possibly the medium in which it occurs.

Supernovae


Caltech

As with primordial black holes, the violent expansion of charged particles from a supernova into the ambient magnetic field would produce a pulse that might be detectable by the ETA. Approximately one supernova event per century is expected in a galaxy.

Compact Object Mergers


NASA/JPL-Caltech/Cornell Univ.

Binary star systems consisting of closely separated compact objects, such as neutron stars and/or black holes will eventually merge as a result of the emission of gravitational radiation and any other energy loss. Such mergers will potentially produce a burst of emission that could be detected in the radio spectrum. Several mergers involving a pair of neutron stars are expected per year in the observable area. Mergers of a neutron star and black hole are expected to be more common, but to generate weaker pulses.

— John Simonetti

For more information,
visit www.phys.vt.edu/~jhs/eta/science.html

Pisgah Astronomical Research Institute (PARI) near Asheville, N.C. Each stand, however, is a carefully situated, dual-polarized, 38-MHz-resonant dipole antenna, individually instrumented and digitized. The complete array continually scans the entire sky using fixed "patrol beams."

The design frequency of ETA was set at 29-47 MHz because of both human and galactic considerations, according to Ellingson International short-wave broadcasting presents strong interfering signals below about 30 MHz and broadcast television interferes above 50 MHz.

"From the antenna perspective, this amounts to about 50 percent bandwidth and would ordinarily mean we should use an ultra wideband antenna," he said. "At these frequencies, however, Galactic emissions are extraordinarily strong and can easily be the dominant source of noise." Ellingson's previous studies had indicated that simple, dipole-like antennas, combined with custom preamplifiers having very high dynamic range and carefully matched to the Galactic noise spectrum, could exhibit the best possible sensitivity with such dominant Galactic noise in this case.

The inputs from the dipole feeds are analyzed by a reconfigurable computing system developed for the project by Cameron Patterson, an associate professor of ECE, who is coordinating the project's computing systems.

The system consists of 16 interconnected Xilinx evaluation boards — each incorporating a field programmable gate array (FPGA) and two PowerPC CPUs. The resulting system is a single, large "virtual FPGA" with 500,000 logic cells and 672 differential I/O signals. The virtual FPGA processes the inputs and forms the 12 patrol beams that scan the skies. The system must also estimate and remove frequency dispersion introduced by propagation through the ionized interstellar medium — an extraordinarily computationally intensive task.

"Compared to the 'stovepipe' signal processing hardware that is traditionally used for radio astronomy, this system gives us greatly increased throughput and a much lower system cost," Patterson commented.

The relatively low cost, and simple design have enabled the team to construct ETA in just months. The project was started in August and calibration begins this spring. "We would like to detect something that hasn't been detected with other instruments within the first year," Patterson said.

Detection of any new transients would have extraordinary implications for the astrophysics field, said Simonetti. "Detection of exploding primordial black holes, mergers of neutron stars, or new sources of giant and nano-giant pulses would be enormously significant — especially if they could be detected on a regular basis," he said. "Once identified, these sources become ready-made laboratories for exploring particle physics at energies unattainable in Earth-bound particle accelerators, and additionally serve as probes of the currently poorly understood structure of the interstellar and intergalactic medium."

"We are building an instrument that is intended to be used — not simply demonstrated — and which will be able to do some exciting science," said Ellingson.

"Nothing compares to the thrill of building a useful working system, especially when it's the first of its kind. The fact that we are also pushing the limits of performance in wideband, high-dynamic range, direct-sampling receivers; reconfigurable real-time computing; and interference mitigation is just gravy."

For more information on ETA, visit the project website at www.ece.vt.edu/swe/eta/

Almost belying its galactic promise, ETA is a visual surprise: it looks like 12 pipes stuck in the grass at the Pisgah Astronomical Research Institute (PARI) near Asheville, N.C. Each stand, however, is a carefully situated, dual-polarized, 38-MHz-resonant dipole antenna, individually instrumented and digitized. The complete array continually scans the entire sky using fixed "patrol beams."