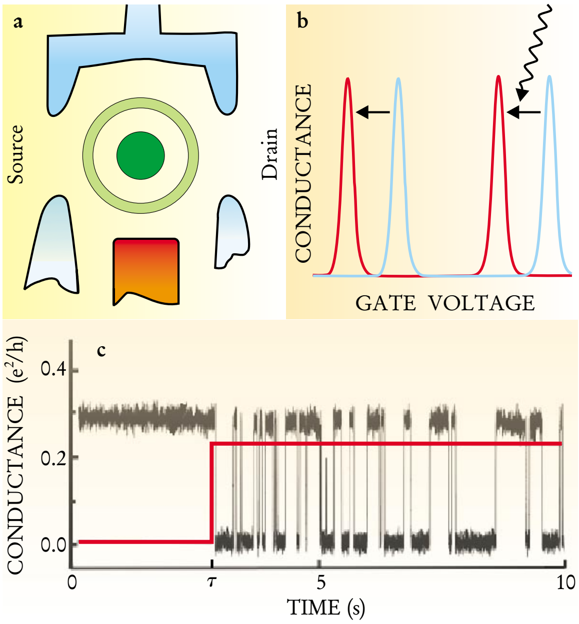

A QUANTUM DOT has been used to detect single far-infrared (FIR) photons. **(a)** The dot is formed in a two-dimensional electron gas. Negatively biased metallic gates (blue) about 700 nm apart confine the electrons laterally. The dot is in a large perpendicular magnetic field, and the electrons in the dot occupy the two lowest Landau levels. The lowest level (light green) forms an outer ring; the second level (dark green) forms an isolated inner core. An additional gate electrode (red) modifies the electrochemical potential of the dot. **(b)** The conduction through the dot (blue curve) is periodic in the voltage applied to the gate electrode. When a FIR photon is absorbed, an electron is excited into the inner core, and the positions of the conductance peaks shift (red). **(c)** Here the gate voltage has been set for an unirradiated conductance peak (a blue peak of **b**). After an FIR source (red) is turned on at time τ, discrete absorption events, which switch off the dot's conductance (black), are observed. (Adapted from ref. 1.)

Jack Hergenrother and his coworkers at Harvard University.[2] Instead of a quantum dot, their device had a small, superconducting island that was connected to normal-metal leads through tunnel junctions and capacitively coupled to a gate electrode. At very low temperatures, the superconducting pairing energy limited the island to only even numbers of electrons. But a sufficiently energetic photon—here, microwave photons of energy 300 μeV—could entice a single, unpaired electron onto the island, enabling current to flow through the island at otherwise nonconducting gate voltages. Direct observation of conductance switching in such a device has yet to be observed, however.

The time resolution in the quantum dot detector experiments is currently limited by the 1 ms time constant of the conductance measurements. Komiyama and his collaborators are investigating using high-speed amplifiers, such as the RF single-electron transistor (RF-SET) electrometer developed by Rob Schoelkopf (Yale University) and his coworkers.[3] This amplifier, which measures the changes in RF power reflected from a metallic SET due to changes in the transistor's gate voltage, has a bandwidth of over 100 MHz and may yield submicrosecond time resolution.

Faster measurement times are not the only ingredient needed to increase the photon counting rate of these devices. As with photomultipliers in the visible and near-infrared, an important characteristic of the quantum dot FIR detector is the time required to reset the device after a photon has been counted. One option to reduce this dead time is to use smaller magnetic fields, which yield shorter lifetimes for the excited electron on the inner core but change the tuning of the detector. A second is to shift the gate voltage to monitor the doubly excited state, in which two electrons have been excited into the second Landau level. Although the coupling to the incident radiation will be smaller for the doubly excited state than the singly excited state, the lifetime of the state is about two orders of magnitude shorter, Komiyama tells us.

Other FIR detection schemes are also under development. Schoelkopf and company have proposed their own FIR detector, which uses an RF-SET to sense the individual pairs of quasiparticles created in a superconductor when FIR photons are absorbed, breaking Cooper pairs.[4] This approach would result in a more broadband FIR detector.

Sensitive FIR detectors will be strongly welcomed by the astronomy community. "Imaging arrays of very sensitive FIR detectors promise to revolutionize observational astronomy," says Harvey Moseley of NASA's Goddard Space Flight Center. "The combination of visible and submillimeter observations will allow us to accurately measure the history of energy release—and hence nucleosynthesis—in the universe as a function of cosmic time."

These detectors may also find other applications, notes Komiyama, such as in near-field microscopy. Recent advances have been reported in the mid-infrared, with wavelengths of 10 μm (see PHYSICS TODAY, July 1999, page 18). "The remaining obstacle for application in the FIR range was the lack of sensitive detectors, which is now resolved in principle by our work," says Komiyama. In any laboratory setting in which such sensitive FIR detectors find application, the radiation source will have to be cold, since the room-temperature blackbody radiation spectrum is peaked in the FIR.

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Survey Halves Estimated Population of Big Near-Earth Asteroids

> NASA's goal is to determine, as soon as possible, the orbits of all asteroids near enough and big enough to threaten cataclysmic damage.

On 1 January 1801, reckoned by sticklers to be the first day of the 19th century, the Sicilian astronomer Giuseppe Piazzi discovered Ceres, the first of the asteroids. With a diameter of almost 1000 km, Ceres remains by far the largest of the known asteroids. Piazzi was searching the region between the orbits of Mars and Jupiter where Bode's law, an empirical formula of the day, said there ought to be an undiscovered planet.

Nowadays there are thought to be

perhaps half a million asteroids with diameters larger than 0.5 km orbiting the Sun within the "main asteroid belt," which extends from 2.2 to 3.3 astronomical units from the Sun. (1 AU $\approx 1.5 \times 10^8$ km is Earth's mean orbital radius.) Yet the total of all their masses is less than 0.1% that of the Earth. The orbits of more than 10 000 of the bigger asteroids, not all of them in the main belt, have been determined and catalogued since 1801.

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A 1-METER-APERTURE TELESCOPE of the kind deployed by the US Air Force for tracking artificial satellites. This one is still in the manufacturer's showroom. The one on Hawaii's Haleakala volcano was used part-time by the Jet Propulsion Laboratory's NEAT project to search for near-Earth asteroids. "They look and move almost like naval gun turrets," says NEAT astronomer Davis Rabinowitz, referring to the unusually rugged mounts needed for the telescopes' rapid repointing requirements.

Too close for comfort

The asteroids are of particular interest to astronomers studying the beginnings of the Solar System. But in recent years they have also aroused a more practical concern: How likely is it that an asteroid big enough to do catastrophic damage will hit the Earth in the foreseeable future? And what, if anything, can we do about it?

Although the great majority of asteroids, residing safely within the main belt, never come within 1 AU of the Earth's orbit, there are families of eccentric asteroid orbits that come much closer, some even crossing our own. Particular attention has been focused on "near-Earth asteroids" (NEAs) with diameters larger than 1 kilometer.

By convention, an NEA is any asteroid that, somewhere in its orbit, comes within 1.3 AU of the Sun. And a diameter of 1 km is thought to be near the threshold for a global catastrophe.[1] The putative asteroid that Luis Alvarez and coworkers blamed, in 1980, for wiping out the dinosaurs some 65 million years ago would have been about 10 km in diameter. Four years after Alvarez's death in 1988, its likely impact crater was identified in the waters off the Yucatan peninsula. (See PHYSICS TODAY, December 1992, page 17.)

NASA has set as a goal the identification of 90% of all NEAs larger than 1 km within the next ten years. The idea is that if we know a decade or more in advance that a kilometer-size asteroid is headed for Earth, a concerted international effort can be mounted to nudge it gradually away from its collision course. People are thinking about tricks like mounting rocket engines or solar sails on a threatening asteroid. Simply blowing it up might do more harm than good. For a much larger asteroid, comparable to one that supposedly ushered in the dinosaur-free Cenozoic era, the task would be far more difficult. But happily, the size distribution of the asteroid population falls steeply with increasing diameter. It is estimated that the Earth is likely to suffer a 10 km asteroid collision only once in the next hundred million years.

A NEAT estimate

In a recent paper,[2] the Near-Earth Asteroid Tracking (NEAT) team at Caltech's Jet Propulsion Laboratory reported a new estimate of the population of NEAs larger than 1 km. Headed by Eleanor Helin, the group has been conducting an automated search for NEAs since 1996, borrowing a US Air Force surveillance telescope on the rim of the extinct Haleakala volcano on the Hawaiian island of Maui for a week or two every month. Designed to track artificial satellites, this 1-meter-aperture Air Force telescope (and half a dozen of its fellows deployed elsewhere) is characterized by a wide field of view and the ability to shift very rapidly between different patches of sky. (See the photo above.) Both of these attributes are particularly desirable for asteroid hunters.

The new survey estimates the total population of NEAs bigger than 1 km to be 700 ± 230. That's only about half the population estimated by earlier surveys. It translates into a probability of about 0.4% that one of these large asteroids will hit the Earth sometime before the end of the third millennium. Factors of 2 in so rough an estimate of so remote a threat are less important than the NEAT team's conclusion that "doubling the current worldwide detection rate [should] lead to near completion in the next decade" of a catalog of all the large NEAs.[2]

The NEAT team built a large-format CCD array to record images in the Air Force telescope's focal plane. In the pre-CCD 1970s, Helin and Eugene Shoemaker undertook the pioneering Planet Crossing Asteroid Survey (PCAS) with photographic imaging at the 0.46 m Schmidt telescope on Mt. Palomar. In those days, astronomers identified asteroids and comets by the streaks they made on time-exposed plates as the telescope tracked the fixed stars. Such photographic surveys required visual inspection of the developed film by a trained observer with a stereoscopic microscope, resulting in inevitable variation of the finding efficiency, depending on the skill—or even the mood—of the film scanner.

The PCAS results disabused astronomers of the comforting assumption that there were very few near-Earth asteroids. Shoemaker, who died in a traffic collision in 1997 while in Australia to study impact craters, was codiscoverer of the comet Shoemaker–Levy, whose spectacular crash onto Jupiter in 1994 did much to raise public concern about the danger of collisions with the smaller bodies of the Solar System.

Estimating an asteroid population from the small subset actually found depends crucially on how well one knows the finding efficiency as a function of brightness and motion across the sky. That's one of the great advantages of a computerized CCD search. The NEAT survey automatically images a patch of sky three times—at 15-minute intervals—and then identifies candidate asteroids by a computer comparison of the three digital images. The 30-minute lever arm yields provisional orbit parameters that can be sharpened by follow-up observations the next night. Determining an orbit from a few observations is a technique that goes all the way back to Newton's colleague Edmund Halley.

One needs the orbit not only for its own sake, but also to estimate the asteroid's size from its apparent brightness. Knowing the asteroid's distance, one can convert its measured brightness into an absolute visual magnitude *H*, which provides an estimate of its diameter.

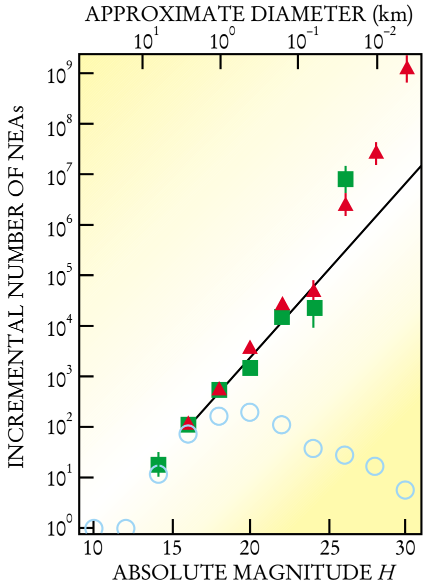
Absolute magnitude in planetary science is not to be confused with the more familiar absolute magnitudes ascribed to stars. Both are logarithmic measures of intrinsic brightness, but they have different reference standards, appropriate to their disparate distance scales. For asteroids, as for any nearby body that shines by reflected light, there are complications of phase (like the phases of the moon and Venus). And there are further complications due to irregular shapes and rapid spins.

The bottom line is that, for the purposes of the NEAT survey, a diameter greater than 1 km translates into $H < 18$. (By ancient convention, magnitude decreases with increasing brightness.) The observed brightness of an asteroid is, of course, proportional to its surface area. But the specific linking of 18th magnitude to 1 km presumes a definite albedo (surface reflectivity)—namely, 10%. Although asteroid albedos vary over a considerable range, depending on surface composition, the NEAT team has concluded that assigning this mean value, in effect, to the entire observed sample is adequate to the task. And it facilitates comparison with earlier searches that made the same approximation.

Correcting for search efficiency

In 33 months of searching before the Air Force reclaimed the Haleakala telescope for upgrading in August 1998, NEAT found 45 NEAs, 26 of which had $H < 18$ and therefore, presumably, diameters exceeding 1 km. To deduce a total population of large NEAs from this modest harvest, the group developed a computer simulation of the detection, by their search system, of asteroids from a large fictitious population with random but realistic orbits. Given the known detection efficiencies of the NEAT system as a function of an asteroid's brightness and angular velocity across the sky, this simulation yielded the survey's net finding efficiency as a function of *H* and thus of asteroid diameter.

Then, to estimate the total NEA population of a given *H* interval, the NEAT team divided the number of NEAs they actually found by the calculated finding efficiency for that interval. The resulting estimates are the green squares in the figure above.



Estimated total population of near-Earth asteroids, plotted as a function of absolute visual magnitude *H* and (top scale) the diameter deduced from *H*. The green and red data points, both corrected for finding efficiency, are from the NEAT and Spacewatch surveys, respectively. Each point gives the population for the two-magnitude interval to its left. The straight line is a fit to the NEAT data for the *H* interval 16–22. The open circles are current raw totals of near-Earth asteroid identified worldwide, uncorrected for finding efficiencies. (Adapted from ref. 2.)

Each point represents the population of the two-magnitude interval to its left. (A decrease of 5 magnitudes is, by definition, a 100-fold increase in brightness.) Thus corrected for detection efficiency, the 26 NEAs brighter than 18th absolute magnitude found by NEAT translate into a total estimate of 700 near-Earth asteroids larger than 1 km.

The red triangles in the figure are the similarly corrected findings of an earlier Spacewatch survey.[3] Spacewatch, the pioneering CCD asteroid search, was organized in 1981 by Tom Gehrels (University of Arizona) and is still in business. With its 36-inch telescope on Kitt Peak, Spacewatch can find fainter objects than NEAT can, but its acquisition rate is limited by the telescope's narrow field of view. NEAT team member David Rabinowitz is also a veteran of Spacewatch. The logarithmic fit to the NEAT data in the *H* range 16–22, indicated by the straight black line on the plot, is consistent with the shape of both data sets. But it should be noted that the Spacewatch data in the figure have been normalized by Rabinowitz to optimize agreement with the NEAT results.

Finishing the job

The open blue circles in the plot show the total world sample of observed NEAs as of last summer, uncorrected for finding efficiencies. In recent months, a large fraction of the world's new finds have been made by Grant Stokes and colleagues at the MIT Lincoln Laboratories, as a by-product of their satellite-tracking work for the Air Force. They locate asteroid candidates by means of an expensive CCD array with very fast data acquisition and readout, mounted on an Air Force surveillance telescope in New Mexico. The coordinates are then posted by the Harvard–Smithsonian Minor Planet Center for follow-up by a worldwide network of amateur and professional astronomers. "Our group has not been involved in estimating populations," Stokes told us.

"After an enforced hiatus of 18 months," says NEAT project manager Steven Pravdo, "We should start looking for NEAs again in a few weeks, with an upgraded CCD camera mounted on a different Air Force telescope on Haleakala—this one with an aperture of 1.2 m. That should let us push our viewing limit to objects fainter by one magnitude."

Meanwhile, NEAT has entered into a symbiotic collaboration with the Palomar Observatory and Charles Baltay at Yale, a veteran particle physicist afflicted, like so many others, with adult-onset cosmology. He and Rabinowitz (now also at Yale) are building a large and elaborate CCD array for the 48-inch Oschin Schmidt telescope on Mt. Palomar. By next year that should provide an extraordinarily wide field of view for NEAT's continuing asteroid search and—on a very different distance scale—for Baltay's quest to determine cosmological parameters by measuring gravitational lensing of quasars by intervening galaxy clusters and dark matter.

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