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Transforming Earthquake Detection?

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together. The results from comet C/2011 N3 (SOHO) are thus pioneering a new method of cometary study.

Understanding the physical construction of comets sheds important light on how matter accreted from tiny, micrometer-sized specks of dust and molecules of gas to build kilometer-sized ice and rock-rich bodies, the comets, in the first million years of the solar system's existence (*9*). This is still a great mystery—most studies of the aggregation of protoplanetary gas and dust, using their known physical parameters (bulk modulus, porosity, surface cohesion, dielectric constant, etc.) at the expected interaction speeds of a few kilometers per second or more, show that particles should build up to millimeter- to centimeter-sized objects quite easily along the plane of the early solar system, but larger-sized particles disintegrate upon impact, creating an "aggregational barrier" to planetesimal formation (*10*, *11*). (On the other hand, once billions of kilometer-sized comet bodies were formed, accretion into the known planetary-sized objects was relatively straightforward.) Since comets are weak bodies formed relatively gently, it is likely they fragment and disrupt into pieces similar to those from which they were assembled. Thus, the size-frequency distribution of sun-grazing comet fragments may be able to provide important information about the formation mechanisms of comets.

Sun-grazing comets also probe a local temperature regime, from 1000 to 4000 K, that is not otherwise encountered in the solar system, emitting material via sublimation and thermal desorption as they do so. Thus, from remote spectroscopic studies of sungrazers, we can learn about the least-volatile components that make up comets (and presumably the rest of the bodies in the solar system), like the rocky silicates and metal sulfides that are some of the first materials to condense out of the protosolar nebula and protoplanetary disk and make up the bulk of Earth and the other terrestrial planets.

The work of Schrijver *et al*. also holds great promise for improving our understanding of the solar corona. By using comets as standard test particles and "running" them through the corona, observations of the passage of many comets at different heights above the photosphere, at different times, and in different solar latitudes and longitudes, will also help us to map out the three-dimensional density structure of the corona in a completely new way, independent of the quasi-static magnetohydrodynamic models used in the past. Understanding how the roiling 5780 K convective surface of the present-day Sun, perfused with magnetic field lines extending out into interplanetary space, creates the $\sim 10^6$ K tenuous corona exosphere is not only the prime goal of NASA's next big solar mission, Solar-Probe Plus, but is also vital to our existence as human beings living 93 million miles away, as this is the region of space where the giant solar flares and coronal mass ejections are created and launched toward the planets.

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GEOPHYSICS

Transforming Earthquake Detection?

Citizen science projects have the potential to transform earthquake science if data quality standards are maintained.

Richard M. Allen

Earthquakes are a collective experience. Citizens have long participated in earthquake science through the reporting, collection, and analysis of individual experiences. The value of citizen-generated status reports was clear after the 1995 Kobe, Japan, earthquake (*1*). Today's communications infrastructure has taken citizen engagement to a new level: Earthquake-related Twitter messages can outrun the shaking (*2*), Internet traffic detects earthquakes (*3–7*) and maps the distribution of shaking in minutes (*8–10*), and accelerometers in consumer electronic devices record seismic waveforms (*11–16*). What are we learning from this flood of data, and what are the limitations? How do we harness these new capabilities for scientific discovery, and what is the role of education?

Modern geophysical instruments can record a magnitude 5 (M5) earthquake from the other side of the world. However, to map, track, and analyze the details of large destructive earthquake ruptures, and to elucidate how the rupture process links to earthquake impacts, requires detailed data from close to the event. Currently, the best traditional geophysical networks only have stations every ~10 km and cover limited areas. Contributions of citizens have the potential to provide much higher resolution, especially in residential areas.

The best-developed citizen-based earthquake science project today is the U.S. Geological Survey's (USGS) "Did You Feel It?" (DYFI) (*8–10*). After an earthquake, individuals can go online and answer questions designed to capture the data necessary to estimate shaking intensity. The location information of each report is converted to latitude-longitude coordinates and the data are mapped. Online tools allow users to explore the data set that includes their contribution. The project also has an educational component explaining earthquake phenomena.

The DYFI database now contains nearly 2 million entries available for download (*8–10*). The DYFI data are used to complement the traditional network data. Combined with reports of building damage, they can also help to determine how well building infrastructure can withstand earthquake shaking in different locations.

An individual's reaction to an earthquake can also be tracked for scientific purposes without that individual's active participation. The European-Mediterranean Seismological Center (EMSC) tracks the hits on its Web site and uses the hit rate and Internet protocol (IP) addresses to extract information about earth-

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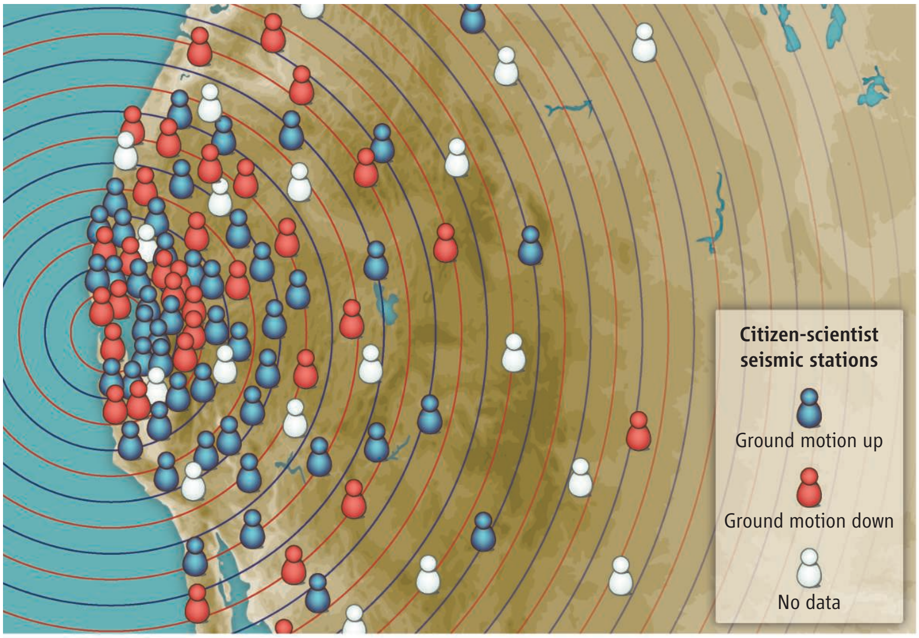

The value of citizen science. New networks allow citizen-scientists to host seismic stations and provide detailed waveform recordings. This instantaneous view of ground shaking looks like ripples on a pond propagating away from the earthquake source. In the future, such data may provide detailed observations of seismic wave propagation and earthquake source processes. The challenge is to maintain data quality and ensure that citizen networks are still active when the next big earthquake occurs.

quake occurrence and the likely affected areas (*6*, *7*). Similarly, the USGS monitors Twitter messages containing the word "earthquake" to detect events (*3*–*5*). This approach detects earthquakes that are broadly felt but provides no accurate location or magnitude information. Research continues into whether intensity information can be extracted from tweets.

Reports of individual experiences are valuable sources of data, but instrumental time series of ground motion contain much more information. Accelerometers that record such data are now embedded in many laptop computers and smart phones. The "iShake Cal" iPhone application records seismic waveforms and transmits them to a central server when it detects an earthquake (*15*, *16*). The Quake-Catcher Network (QCN) uses the accelerometers in laptop computers to collect data in a similar way (*11*, *12*). The accelerometers in both the iShake phones and the QCN laptops are orders of magnitude less sensitive than the instruments in traditional networks, and earthquake signals must be separated from everyday movements. However, for events of M5 and greater, the signals are strong enough to be clearly recorded, provided that the laptop or phone is within tens of kilometers of the epicenter and is stationary at the time of the quake.

USB accelerometers that plug into desktop computers and cost tens of dollars are an improvement on embedded instruments. The sensor can be glued to a basement or the wall of a building, providing better coupling to ground or building motion and allowing detection of M3 earthquakes. Both the Community Seismic Network (CSN) and the QCN deploy such sensors in citizens' homes in earthquake-prone regions (*11*–*14*). The USGS NetQuakes project uses a more robust system with a higher-quality sensor. An engineer bolts the ~$6000 sensor package to the concrete basement of a home; the instrument is largely autonomous, needing only periodic connections to the citizen-host's wireless Internet. Online tools allow the citizen-scientist to look at the recorded data and compare recordings across the region (*17*).

This new age of networks has the potential to increase the density of instruments by an order of magnitude or more. Data from a recent deployment of 5000 sensors in a 5 km by 7 km area in Long Beach, California, by NodalSeismic Inc. show that as the seismic energy from nearby earthquakes radiates across the array, it deviates from the simple waves-on-a-pond pattern, indicating the complexities of the subsurface structure (*18*). Dense data like this across swaths of earthquake-prone regions could substantially advance understanding of wave propagation effects and the earthquake source (see the figure). In addition, sensors can be placed in different types of locations, such as multiple stories of different types of buildings. Finally, this approach provides one of the best opportunities to engage citizens to learn about earthquakes.

However, the challenges are substantial. First, how good are the data? Some sensors may record true ground or building motion, whereas others record the oscillations of a wobbly tabletop. Second, how robust will the networks be? How many will lose power or data in a large earthquake? And will they still be running by the time a large earthquake occurs? Long-term operation requires continued interest of the citizen-hosts to ensure that both hardware and software remain operational. Finally, privacy concerns may limit data use if individuals are not prepared to release precise sensor locations.

Despite these challenges, citizen-based projects have the potential to transform earthquake science if two conditions are met. First, amateur scientists must be able to explore the data and draw conclusions. Online educational tools such as those at DYFI allow individuals to see how their data are used and how they contribute to scientific discovery. This is crucial for maintaining continued participation. Second, the citizen-generated data must conform to high data management standards with accurate location and instrument type information. It must also be archived alongside traditional data in order to be useful to professional scientists and thereby drive fundamental discovery.

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