methane is abundant in interstellar space, researchers had expected it would be abundant in the early solar system, and hence in comets.

So far, astronomers haven't been able to detect anything more than hints of the compound in comets. But Mumma and his team, using a more sensitive instrument, had two advantages: Hyakutake's brightness and its rapid motion relative to Earth, which Doppler-shifted its methane lines away from the signature of methane in Earth's atmosphere, making them possible to detect. The team first detected methane on 23 March and calculated that it makes up about 1% of the comet's ice.

The team then searched for methanol, which earlier observers had been able to detect in comets because it is so abundant, amounting to about 5% of their ice. But the methanol lines that appeared in Hyakutake were weak, implying that it contains about a tenth as much methanol as other comets. When the researchers adjusted their equipment to search for stronger methanol lines, however, they were shocked to see bright emission lines from an unknown gas. "This was really astonishing," Mumma says. "It was obvious that we had a major discovery on our hands." Extensive database searching and more tests finally proved the gas to be ethane. More important, the ethane level in Hyakutake was nearly 1%, close to that of methane.

This unusual chemistry poses a direct challenge to existing ideas about comet formation in the early solar system. According to one long-standing theory, comets formed from unaltered interstellar ice grains. But Hyakutake can't have originated that way, because methanol is found at higher levels in interstellar space and ethane is unlikely to be made under the same conditions. At the same time, it also challenges another theory, which holds that the early sun first vaporized interstellar ice, which later condensed onto grains that became comets. The chemical reactions expected to take place during the gaseous phase of this process would have left the comets with 1000 times more methane than ethane.

One possibility, say Mumma and his colleagues, is that the primordial cloud of gas, dust, and ice that collapsed to form the solar system had regions cold enough to prevent methanol formation, yet convert acetylene to ethane. Ethane-rich comets would then preserve ice grains from specific regions of the primordial cloud. But for this chemical diversity to have been preserved in comets, the cloud would have had to collapse without being mixed and homogenized.

Instead, Mumma and his colleagues favor what he calls the processed interstellar ice model, in which the chemical diversity formed later, after the primordial cloud collapsed to form the solar system. Ultraviolet radiation from the early sun, they say, could have driven low-temperature chemical reactions in the ice grains, breaking the bonds in methane and turning it into ethane, while destroying methanol at the same time. Hydrogen atoms freed in the first step would then have converted the acetylene to ethane.

"I think [that picture] is entirely reasonable," says Yvonne Pendleton, an astrophysicist at Ames Research Center in Moffett Field, California. "What we needed was a good comet to come along so we could verify it." The theory implies that comets with high ethane levels, like Hyakutake, originated closer to the early sun, perhaps in the Jupiter-Saturn zone. Comets with more methanol, like most of the others analyzed so far, may have originated farther out, near the present positions of Uranus and Neptune, where the ice grains would have been exposed to less radiation and retained more of their original, interstellar composition.

Later, the gravity of the newborn planets would have hurled the comets like pebbles from a slingshot into the far reaches of the solar system, where they now reside. But if Mumma and his colleagues are right, they contain a scrambled record of the chemical diversity within the primordial solar system. Future cometary visitors may add new pages to that record.

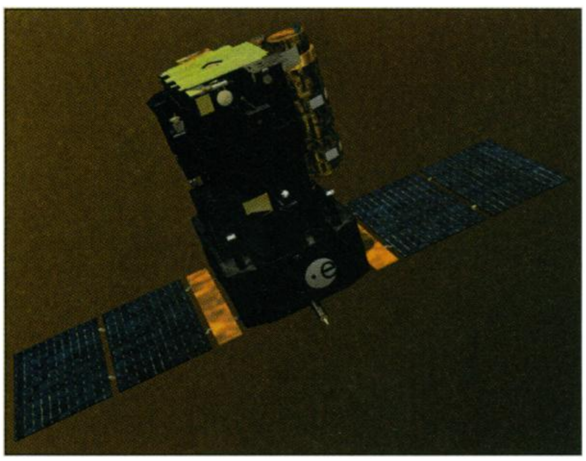
–Kim Peterson

SOLAR PHYSICS

SOHO Probes Sun's Interior By Tuning In to Its Vibrations

To eavesdrop on the sun, it's best to find a very, very quiet perch. SOHO, the solar observatory launched by the European Space Agency (ESA) last December, has just that: a listening post 1.5 million kilometers sunward of Earth, well away from the turbulence of the atmosphere, where it can tune in to the sun 24 hours a day. SOHO carries experiments studying everything from the sun's corona and magnetic field to the solar wind (*Science*, 10 May, p. 813). But three of the spacecraft's 11 instrument packages are devoted to listening: detecting the sun's vibrations, which hold clues to its structure, from the turbulent surface layers all the way down to the nuclear furnace at its heart.

Solar physicists are already hard at work applying this strategy, called helioseismology, from the ground, through a global network of telescopes called GONG (see Articles, this issue). But while ground-based observations are cheaper and more flexible, solar physicists say the only way to pick up the sun's subtlest notes is to go into space. "The community recognized 20 years ago that we needed a vantage from space in order to do helioseismology correctly. We also needed the ground-based network [GONG], and now we are in the fortunate position of having both," says GONG scientist Jack Harvey of the National Solar Observatory (NSO) in Tucson, Arizona. They are already finding out just how fortunate. At last week's American Geophysical Union spring meeting in Baltimore, SOHO researchers reported results from the satellite's first 4 months, including records of known oscillations that far surpass the clarity of ground-based measurements and new insights into the churning of the sun's outer layers.



ESA

Patient listener. The SOHO spacecraft.

SOHO, like ground-based telescopes, can only "listen" to the sun's vibrations indirectly: by monitoring their effects on the sun's surface. By watching for fine-scale undulations, for example, one of SOHO's three helioseismology experiments, the Solar Oscillations Investigation (SOI), is detecting the sun's equivalent of seismic waves, which hold clues to small-scale structures just beneath the sun's surface.

SOI monitors the solar surface by sending sunlight through a filter that transmits only a very narrow wavelength range, centered on an absorption line of nickel, an element found on the visible surface of the sun. The light then falls on a charge-coupled device (CCD), a very sensitive electronic detector, that has 1 million pixels, 700,000 of them occupied by the solar image. If the gases at the solar surface move toward or away from the SOHO spacecraft, the frequency of the nickel absorption line shifts because of the Doppler effect, changing the amount of light that has the right frequency to pass through the narrow-band filter. The Doppler shifts translate into varying intensities on the CCD's pixels. The result, says SOI co-investigator John Leibacher of the NSO, is "a velocity picture of the sun." Each pixel tracks the velocity of a small area on the solar surface.

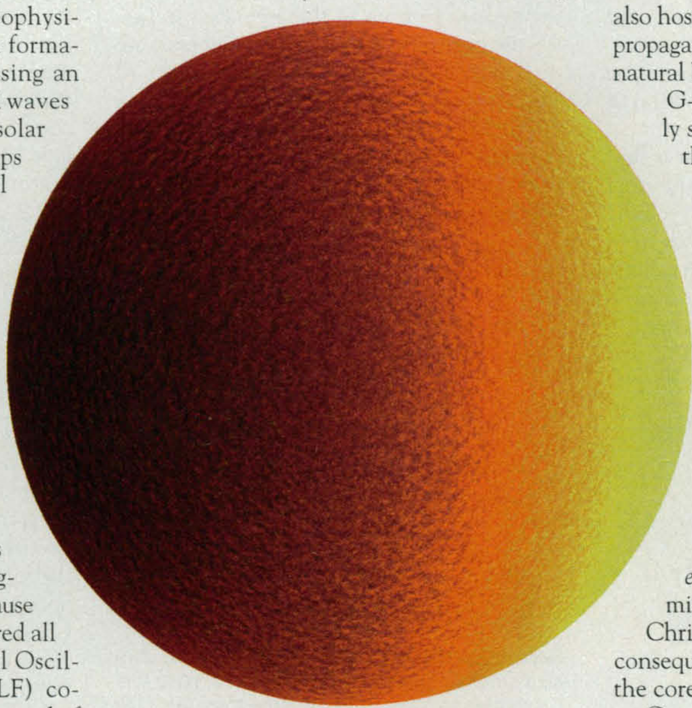
The undulations in turn reveal the travels of acoustic waves as they traverse shallow layers of the sun, then get refracted toward the surface. And just as geophysicists can derive the nature of rock formations beneath Earth's surface by using an array of geophones to pick up sound waves from an earthquake or explosion, solar physicists analyzing the velocity maps expect to build a three-dimensional image of the structure beneath the solar surface.

"We compare the time sequences of the wave patterns. We can see the travel time of the waves from one point to a nearby point as they start into the interior and come back up again," says SOI's principal investigator, Phil Scherrer of Stanford University. Changes in density and flow direction affect the travel times, allowing investigators to look for such things as subsurface flows driven by magnetic fields and convection. "Because we have 700,000 'geophones' scattered all over the sun," says SOI and Global Oscillations at Low Frequencies (GOLF) co-investigator Jørgen Christensen-Dalsgaard of Århus University in Denmark, "we are in a position to know the interior of the sun better than we can ever know the interior of the Earth—my geophysical friends are envious."

Already, Scherrer reported in Baltimore last week, SOI has revealed convection-driven flows beneath the surface. And there's more to come, he says: "We have gathered data that will give us a chance to see some flows around sunspots."

To look deeper into the sun, helioseismologists have to detect oscillations that affect the entire sun at once—a phenomenon more like the ringing of a bell than a seismic wave on Earth. Such resonances shake the sun to much greater depths, but because they affect broad regions of the sun, they can be harder to detect than local oscillations. "More stability is needed since we are no longer comparing the measurements made at one point on the sun with a point elsewhere on the sun," says Harvey. "We are making absolute measurements, which is much harder than differential measurements." What's more, the speed at which they displace the sun's surface can be no more than a few millimeters a second.

Ground-based observations have detected the strongest of these global oscillations, which can raise and lower the sun's surface by a few hundred meters over periods ranging from minutes to hours. But with SOHO, helioseismologists hope to detect many more resonances, building up a detailed picture of the solar interior. Their hopes ride on two instruments: the GOLF instrument, which detects global motions by monitoring Doppler shifts in a sodium absorption line, and the Variability of Irradiance and Gravity Oscillations (VIRGO), which monitors the minute variations in luminosity that result as the solar oscillations alternately compress and rarefy the gases at the solar surface.



STANFORD

Sound picture. Subsurface vibrations shake the surface of the sun, producing dark (rising) and bright (falling) patches in this image from SOHO's SOI instrument.

Working in favor of both experiments are the quiet vantage of space and an unusually quiet sun. Convection at the sun's surface, which produces the visible solar granulation, also roils it like a pot of boiling water, making the task of detecting the subtle motions resulting from global oscillations even harder. BISON, the Birmingham Solar Oscillation Network, an array of instruments that began measuring solar oscillations at six ground-based sites in 1981, reported a few years ago that this solar noise was substantially lower than expected—a finding the VIRGO and GOLF teams have now confirmed. "This means that we have a 10 times better chance of pulling out significant low-frequency global oscillations than we thought we would," says GOLF principal investigator Alan Gabriel of France's Institute of Space Astrophysics in Orsay.

So far, as Gabriel reported in Baltimore, GOLF has detected the so-called 5-minute p-modes—the first solar oscillations ever discovered, in 1960—"with a quality that is far superior to what is obtained on the ground." That sensitivity is raising investigators' hopes of detecting a set of oscillations that have eluded observers so far: the so-called g-modes. Although all of the local and global oscillations detected so far are acoustic, or pressure waves, the sun should also host buoyancy waves—g-modes—which propagate as material oscillates around its natural buoyancy level within the sun.

G-mode oscillations have been ardently sought by helioseismologists because they would penetrate the deepest regions of the solar interior. "They would really allow us to nail down the conditions in the core," says Scherrer, perhaps solving the riddle of why the sun seems to produce fewer neutrinos than predicted from the calculated fusion rates in the sun. P-modes observed from Earth are already suggesting that theorists may have to revise their picture of the sun's nuclear furnace. "We have some evidence from the GONG results presented in this issue of *Science* that there might be some slight mixing in the core of the sun," says Christensen-Dalsgaard. "That would have consequences for the energy generation [in the core]."

G-modes "don't stick out like those p-modes," says Claus Frölich of the Physical-Meteorological Observatory of the Devos World Radiation Center in Switzerland, principal investigator of VIRGO, because their amplitudes are expected to be weak. But the sun's calm demeanor and SOHO's performance so far have convinced the majority of helioseismologists that the g-modes will soon rise out of the noise. Indeed, they may already be hidden in the data collected over the last few months, most of which is still awaiting processing. Cambridge University's Douglas Gough, co-investigator on all three helioseismology experiments, who coined the term "helioseismology" in 1983, is so convinced that g-modes will pop up in SOHO data before the year 2000 that he has placed a bet with one of his colleagues. The stakes: two bottles of premier-grand-cru claret. "Absolutely, I shall win the bet," he exclaims. Patient listening will have its rewards.

–Alexander Hellemans

Alexander Hellemans is a science writer in Brussels.