and coalescence of the newly formed clusters can be profound—in principle, even producing clusters with tens of thousands of atoms. This makes the process an effective protocol for creating clusters of controlled sizes from practically any metal. By adjusting the buffer thickness, for instance, one can potentially tailor the size and density of the nanostructures that drop to the surface,[4] as well as the profile of the grating.

Clean lithography

To measure those grating profiles directly, Asscher and Kerner switched from potassium to gold films. The first scanning force microscopy images of Au on Ru show thin wires that consist of condensed clusters (panel e). Characterizing the properties of such wires (including their conductivity as a function of wire width) remains to be done. While initially diffusing on Xe, the clusters remain balled up, essentially out of contact with the Ru. But after landing, the extent to which clusters wet the substrate depends on their relative surface energies. And the thickness and coverage of molecules could be critical to the morphology of deposited material.

By adjusting the Bragg scattering angle and the laser's power density, Kerner has created patterns of lines that differ in widths and spacing. Because the desorption rate of ablated atoms depends exponentially on temperature, higher power densities sharpen the lines. Asscher points out that their method has the potential to form wires 30 nm wide and 5 mm in length—a 10^5 aspect ratio—using a single laser pulse.

In that respect, the work parallels conventional lithography: The laser wavelength accounts for how finely wires or circuit elements can be drawn. (Using an electron-beam or x-rays, even finer resolution is possible.) Columbia University's Tony Heinz argues that what really distinguishes patterning methods like Asscher's from more traditional photolithography is the chemical purity of the technique: "No one would claim traditional lithography is clean to the last monolayer. But this [method] is. . . . The xenon buffer layer vanishes without a trace."

Asscher envisions a time when vacuum chambers might replace clean rooms in lithographic facilities. But Heinz sees the technique's attractiveness more in terms of doing rigorous, well-controlled surface science. Fabricated in ultrahigh vacuum, for example, the patterned lines provide a template for studying carrier transport of simple molecules and exotic clusters in confined channels. But other projects come to mind as well: measuring crystal growth and diffusion of clusters of different sizes, or monitoring the reaction of one structure with another; in short, the kind of projects that prompted Asscher to develop the patterning method in the first place.

Mark Wilson

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Is Sedna's Strange Orbit the Shape of Things to Come?

A newly discovered distant minor planet may provide clues about the Sun's early environment.

According to Inuit legend, the goddess Sedna lives beneath the frigid Arctic seas. And so in late 2003, when Caltech's Michael E. Brown, working with Chadwick Trujillo of the Gemini Observatory and David Rabinowitz of Yale University, discovered an outer Solar System object whose surface temperature never rises much above 30 K, they proposed that it be named after the Inuit deity.[1]

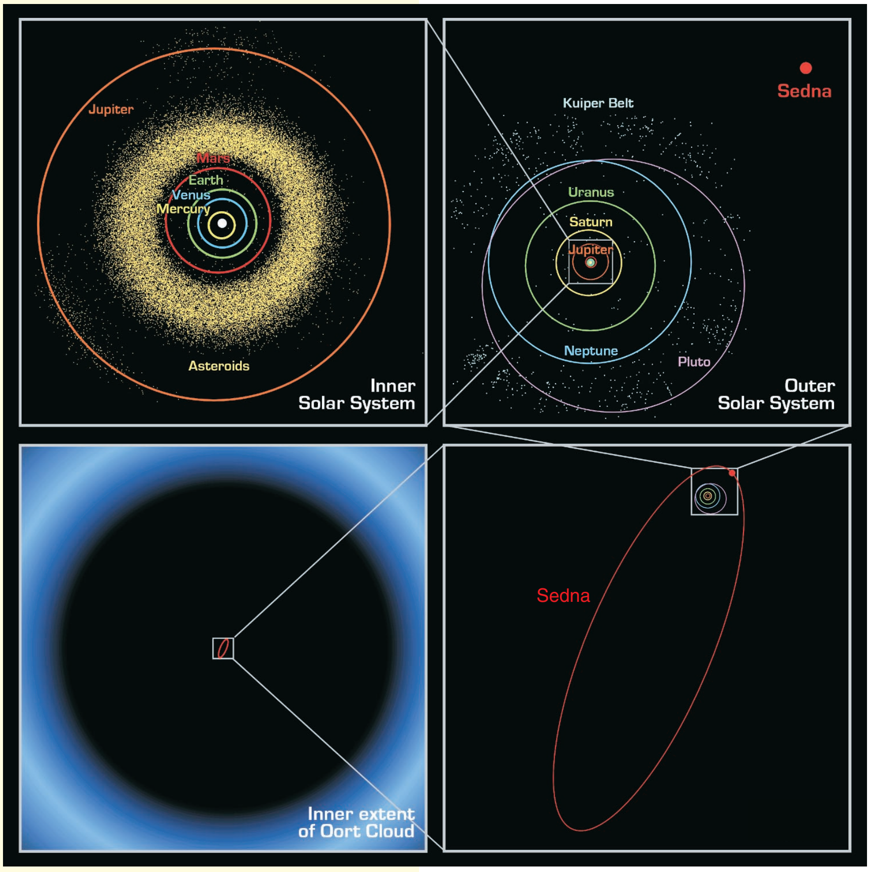
The minor planet Sedna, whose official designation is 2003 VB_{12}, has a number of interesting properties. It is red like Mars, roughly 1500 km in diameter, and has a rotational period much longer than is typical for minor planets. But it is Sedna's record-breaking perihelion combined with its highly eccentric orbit that have planetary scientists most intrigued. If, as expected, other Sedna-like objects are soon found, the clues they leave promise to change scientists' view of the Solar System.

How orbits change

Since the autumn of 2001, Brown and colleagues have systematically observed the sky, searching for reasonably large and bright objects moving across the field of stars and galaxies. In any given observation, they train a 172-megapixel camera mounted on Palomar's Samuel Oschin telescope on a 10 square-degree section of sky. The camera, a mosaic of 112 charge-coupled devices (CCDs), takes three pictures over a three-hour period. By aligning the pictures so that the stars and galaxies overlap, Brown's team can look for moving objects. One such object was observed in the pictures taken on 14 November 2003, and Sedna's discovery was announced publicly on 15 March 2004. Although the idea behind the search is simple, the technology is not. It would have been extremely difficult to discover Sedna with CCDs and computing power from as recently as five years ago.

After they discovered Sedna, Brown and colleagues studied about three years of archival data to determine its orbit. Sedna lies well beyond the distant giant Neptune; it ventures no closer than about 76 AU from the Sun and its semimajor axis is about 480 AU. (The astronomical unit, or AU, is the mean Earth–Sun distance.) Having a semimajor axis greater than Neptune's, though, is hardly a mark of distinction. Planetary scientists now know of some 800 objects in the outer Solar System lying in the so-called Kuiper belt; the most famous of these is Pluto (see the article by Brown in PHYSICS TODAY, April 2004, page 49).

Some Kuiper belt objects—the ones with relatively circular orbits—may have formed in place. The higher-eccentricity objects, it is believed, had their orbits perturbed by gravitational interactions with Neptune or other giant planets. In many cases, that interaction is a scattering process. Scattered Kuiper belt objects have perihelia of about 30 AU, which corresponds to the radius of Neptune's orbit. Other Kuiper belt objects were resonantly captured by Neptune and locked into orbits whose period is a simple rational multiple of Neptune's. The most distant resonance is at 55 AU. The Kuiper belt has an edge at around 50 AU in the sense that all Kuiper belt objects, even if they occasionally stray well beyond 50 AU, lie on orbits with perihelia within that limit. Sedna is the only known object



Sedna's orbit is unusual. The eight planets (upper panels) have nearly circular orbits. Pluto (upper right panel) and some other Kuiper belt objects have reasonably eccentric orbits, but Sedna, which lies outside the Kuiper belt, shows extreme eccentricity (lower right panel). Objects whose orbits have been significantly perturbed by stellar torques lie in the Oort cloud (lower left panel) far beyond the reach of Sedna. (Illustration by Robert Hurt of NASA's Infrared Processing and Analysis Center.)

whose orbit never crosses that edge from beyond.

When gravitational interactions cause an object to have a sufficiently large semimajor axis, a second perturbing effect comes into play. Galactic tidal forces or passing stars can exert a torque that leads to perihelion increase. In the course of an object's wandering, the inclination of its orbit will also be perturbed. Thus, objects whose perihelia have increased to the point that planetary perturbations are no longer in play form a nearly isotropic cloud—the Oort cloud—whose inner edge has traditionally been considered to be several thousand AU from the Sun. The cloud is named after Jan Oort, who in 1950 considered the origin of long-period comets and deduced the existence of a distant spherical cloud of objects surrounding the Solar System.

The mystery of Sedna's orbit is that it could not have formed in place with such an eccentric orbit, yet its perihelion is too large to be accounted for by the scattering processes that yield Kuiper belt objects, and its semimajor axis is too small for stellar torques to have increased its perihelion to 76 AU.

Forensics

The figure above shows a hierarchy of Solar System orbits, from those of the terrestrial planets to those of Oort cloud objects. Sedna's status as lying well beyond the Kuiper belt and well short of the Oort cloud is evident. Although Sedna is currently a one-of-a-kind object, planetary scientists have reason to hope that soon they will know of many more objects living outside the Kuiper belt. For one thing, Brown and colleagues have surveyed only about 20% of the sky. For another, Sedna's diameter of about 1500 km and current distance of about 90 AU put it near the limits of what Brown and company can see. Objects significantly smaller or more distant would not have been caught by Brown's survey, but may be seen by more powerful telescopes.

Once other Sedna-like objects are found, planetary scientists may be able to deduce the mechanism that put them in place. Hal Levison of the Southwest Research Institute compares a population such as the Kuiper belt or the population perhaps heralded by Sedna to the clues left at a crime scene. "As forensic scientists use blood splattered on the wall, so planetary scientists use orbital elements," he says.

Brown and colleagues identify three different mechanisms that could put an object into an orbit like Sedna's. Each mechanism would impress a distinct signature on a population of Sedna-like objects.

It could be that the Solar System contains an as-yet undiscovered planet orbiting the Sun at something like 70 AU (see reference 1 for an interesting discussion of just what defines a "planet"). Just as gravitational interactions with Neptune yield a population of objects in the Kuiper belt, gravitational interactions with that putative planet would lead to a second belt that included a large population with perihelia near 70 AU. Brown and colleagues have already surveyed a large fraction of the sky in the region where a planet would most likely be found, so they deem it unlikely, but not impossible, that a large planet will be discovered.

The other two mechanisms involve stellar encounters: Objects can be put into orbits like Sedna's by interactions with a single star or by multiple interactions with a cluster of stars. Although stellar interactions are rare in the current solar environment, most stars appear to form in clusters where the density is up to 1000 times greater than in a normal galaxy. Thus, encounters with stars could have been reasonably common in the early life of the Solar System.

Only a limited range of stellar trajectories can bounce an object into an orbit like Sedna's from an orbit like that of a Kuiper-belt object. Once other Sedna-like objects are found, one can ask if a single star is compatible with all their orbits. If so, that would be good evidence, says Brown, that an interaction with an individual star did indeed put Sedna and its relatives in place.

In contrast, encounters with many cluster stars would tend to create an isotropic population of perturbed objects, just as stellar interactions lead to a nearly isotropic Oort cloud. Thus, if future discoveries yield objects with a wealth of inclinations, eccentricities, and perihelia, that would be evidence that the Sun began life as part of a dense cluster. Just how dense might be determined by the details of Sedna's and its relatives' orbits.

Clouding Oort's definition

Almost four years before Sedna was discovered, Lowell Observatory's Deep Ecliptic Survey found 2000 CR_{105}, an object on a highly eccentric orbit with a perihelion of 45 AU. That object, unlike Sedna, could be accommodated—albeit just barely—by mechanisms invoked by Rodney Gomes (Observatório Nacional, Brazil) to explain the population of the Kuiper belt. But the discovery of Sedna invites a new look at 2000 CR_{105}; perhaps it, too, is hinting at stellar encounters in the early Solar System. Levison and Alessandro Morbidelli of the Observatoire de la Côte d'Azur considered a number of alternates to the Gomes mechanisms and found a stellar encounter to be the only satisfactory one.[2] They did not, however, consider encounters with more than one star.

Brown has suggested that Sedna and 2000 CR_{105} might be members of an "inner Oort cloud." His view is that the Oort cloud should be defined as the population of objects that got put in place via forces external to the solar system. Other researchers, such as the Southwest Research Institute's Alan Stern, would reserve the term "Oort cloud" to describe the distant population of objects described in Oort's 1950 paper. As Levison points out, Sedna is an object that does not fit neatly into the categories scientists readily had in mind at the time of its discovery.

In that regard, Sedna is reminiscent of Pluto. "When I was in school," recalls Stern, "I was taught that there were four rocky planets, four gas giants, and this oddball Pluto that doesn't fit into any context. Then we saw that Pluto was the tip of a rich iceberg—the Kuiper belt—that had not been discovered and that fits very well into context after all. Now we're finding even more richness much farther out."

Steven K. Blau

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Lampreys Rely on a Molecular Switch to Detect UV Light

By applying a combination of biochemical and biophysical techniques, researchers have identified a UV-sensitive photoreceptor in the pineal gland of the Japanese river lamprey.

Our biological clocks, like those of other vertebrates, keep time thanks to the response to sunlight of the pineal gland. Stuck underneath our cerebral hemispheres, the lentil-sized gland can't detect light directly. Rather, it receives signals from our eyes via a tortuous circuit of nerve cells. Whatever pineal photosensitivity our ancestors once enjoyed lost out to a higher evolutionary priority: boosting the computing power of the mammalian brain.

But the pineal of lower vertebrates is both closer to the top of their heads and better equipped to detect light. In lizards, for example, the pineal corresponds to an eyelike organ that lies beneath the skin and between the eyes.

Intrigued by this light-sensing ability, biologists wondered whether it might be linked to mysterious functions that humans and other mammals no longer perform. Experiments ensued and, from the late 1960s onward, revealed that the pineal glands of certain species of fish and amphibians can detect UV light.

For setting a biological clock, using UV would make sense. The ratio of UV to visible light is higher in twilight than in daylight. However, despite its potential utility, the pineal's UV sensitivity has not been definitively linked to a biological purpose.

On the molecular front, things are a little clearer. By the early 1990s, biologists were close to identifying the photoreceptor molecules responsible for pineal photosensitivity. Evidence suggested that pineal photoreceptors share the same molecular plan as the photoreceptors that mediate vertebrate vision.

In visual photoreceptors, a bulky transmembrane protein called an opsin envelops a light-sensitive derivative of vitamin A called retinal. Free retinal absorbs maximally in the UV, but the electrostatic influence of the opsin shifts the absorption. Depending on what amino acids abut the retinal, the absorption maximum lies anywhere between the UV and the red.

At first, biologists hoped they could identify and isolate pineal photoreceptors by looking for genetic sequences that resemble those of the more familiar visual photoreceptors. That strategy proved difficult to pursue because the resemblances are not as strong as originally expected. But in 1994, Toshiyuki Okano of Tokyo University succeeded in identifying a photoreceptor cloned from chicken pineal. Other identifications of pineal photoreceptors followed: in the trout,

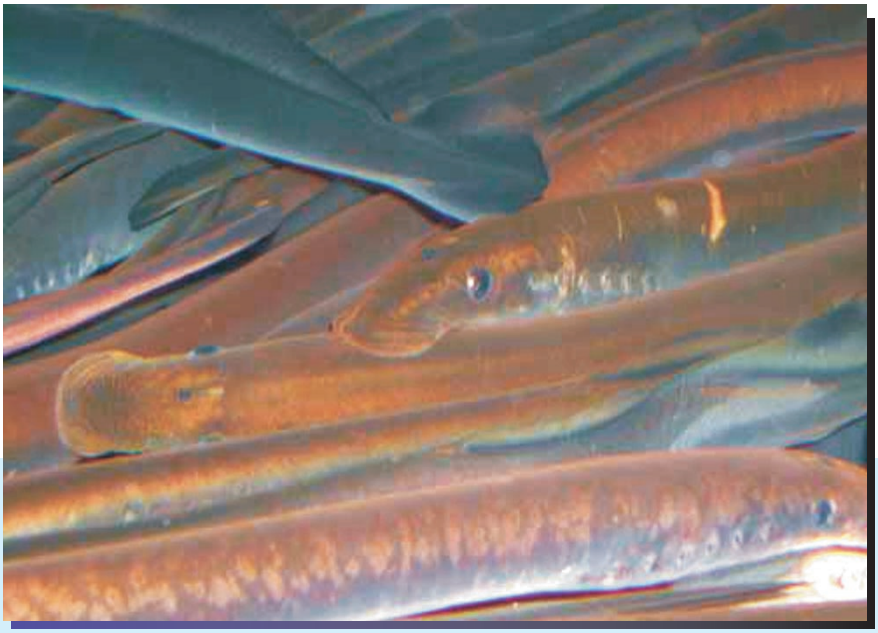

Figure 1. Japanese river lampreys grow to be about 20 cm long. For food, they latch their suckerlike mouths onto other fish to withdraw their victims' blood. (Courtesy of Akihisa Terakita.)