Research in Progress

Potential Planets?

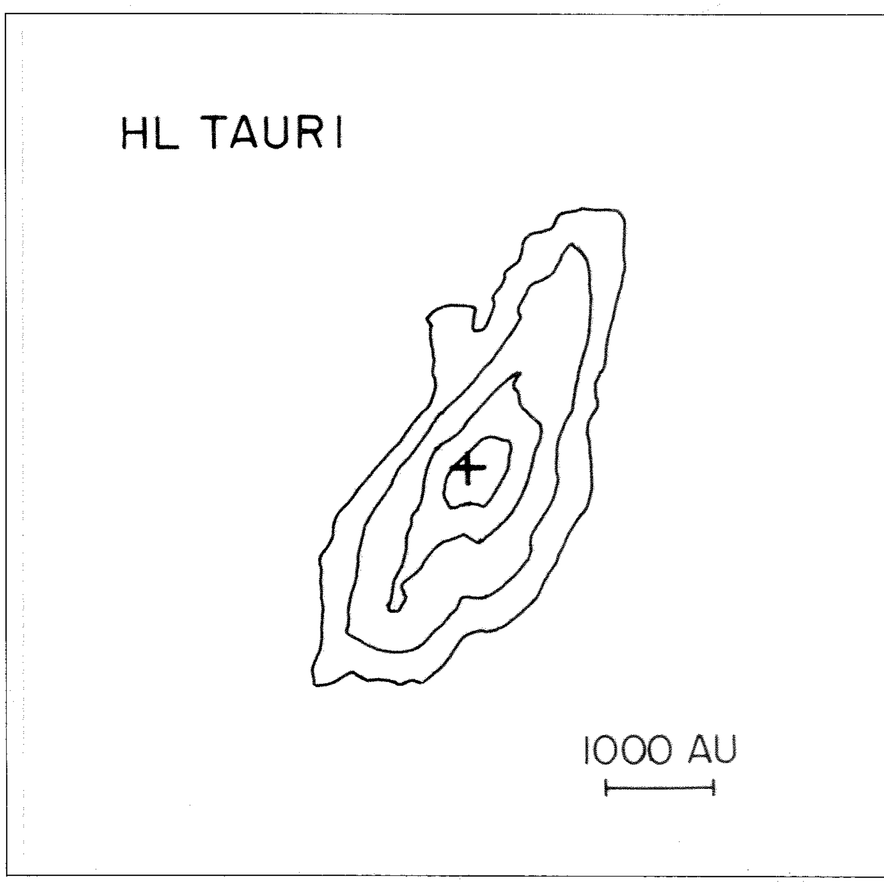
FIVE HUNDRED LIGHT YEARS from here, a star called HL Tauri may be in the process of forming a planetary system. This star, a younger cousin of our own sun, is surrounded by a large disk of dust and gas that is orbiting in accordance with Keplerian laws of motion. This, at least, is the conclusion of a study conducted by Anneila Sargent, a member of the professional staff, and Steven Beckwith, a Cornell University astronomer, using the Owens Valley Millimeter Wave Interferometer.

Over the past few years *infrared* astronomy has revealed circumstellar disks of dust surrounding about half a dozen nearby stars — the dust disk around HL Tauri made news two years ago when Beckwith and his colleagues first discovered it with high-resolution infrared measurements. But by using *radio* astronomy techniques, Sargent and Beckwith have greatly extended their knowledge of HL Tauri with the first direct demonstration that the star's dust disk is accompanied by a disk of gas. Moreover, they were able to prove that the gas close to the star rotates faster than the more distant gas, just as Kepler's laws predict.

This result marks one of the most significant discoveries yet made with the newly constructed Owens Valley Millimeter Wave Interferometer. The interferometer consists of three radio telescopes, each 10.4 meters in diameter. By separating these telescopes by distances of 15 to 100 meters and directing them to the same point in the sky, the astronomers can increase the resolution of their millimeter-wave measurements more than ten-fold, making the three elements of the interferometer the equivalent of a single radio telescope 100 meters in diameter. This makes it possible to see structure on a scale of about 900 astronomical units. The gas disk has a total diameter of 3,000 AU. (1 AU is equal to the distance between the earth and the sun — 93 million miles.) Sargent and Beckwith made their observations between January and March 1986, in five 10-hour stretches.

The infrared measurements made two years ago have a substantially higher resolution than these new millimeter-wave measurements, enabling the identification of the inner radius of the dust disk, which extends just over 100 AU from the star. But dust emits infrared energy in a continuum, making it impossible to determine velocity by Doppler-shift measurements of the infrared data.

The carbon monoxide molecules in the gas disk, on the other hand, emit radio waves at specific frequencies. Because of the Doppler effect, these emissions are shifted to longer wavelengths as the gas recedes from us and to shorter wavelengths as it approaches. By measuring the degree of shift in the wavelength of the radio emissions, Sargent and Beckwith determined that the pattern of velocities in HL Tauri's circumstellar disk is the same as the pattern we see among the planets of our own solar system, where



Five hundred light years from earth, the star HL Tauri (at the cross in this illustration) is surrounded by a large disk of gas and dust. Recent studies with the Owens Valley Millimeter Wave Interferometer have revealed that this disk orbits in accordance with Kepler's laws of planetary motion.

the inner planets move faster than the outer ones.

Current theories of stellar evolution hold that newly formed stars will be surrounded by some of the material from which they are made. This "placental cloud" of gas and dust should be distributed in a flattened disk bound by the star's gravity. As this disk orbits the star, it may begin to coalesce, leading to the formation of planets.

According to current theories of stellar evolution, not all stars will have circumstellar disks that obey Kepler's laws, and not all stars will form planetary systems. Says Sargent, "We plan to examine a sample of other nearby young stellar objects to see what percentage of gas disks have HL Tauri-like velocity structures. Gas may be superficially in a disk-like shape on the plane of the sky, but when we look at the velocity structure within it, we may see a very different velocity structure that would not indicate a planetary system."

According to Sargent, the astronomers are already looking at even more detailed infrared images of HL Tauri — images at resolutions of 50 AU. These suggest that the dust disk may not have a completely smooth elliptical shape. And new receivers at Owens Valley will soon permit them to examine the gas disk at a higher radio frequency. "In addition to doubling the resolution, this will allow us to make some estimate of the size of the dust grains and better ascertain the mass distribution within the disk. And that will enable us to constrain the models that are made of certain kinds of stellar systems — low mass stars about the size of our sun. Of course, we will have to examine circumstellar disks around many more stars to build up an adequate statistical sample. If the National Science Foundation provides funding for three additional radio telescopes to be incorporated into the Owens Valley interferometer, such a study could be accomplished within three years." □ — *RF*

Echoes of the Earth's Core

LOOK INTO ANY ELEMENTARY treatise on geology and you'll find an illustration that makes the earth look something like an onion. This illustration will be labeled with the names of the earth's concentric layers: the crust, 50 kilometers in depth; the mantle, extending down to 3,000 km; and the outer and inner cores, occupying the remaining 3,400 km or so down to the center of the earth.

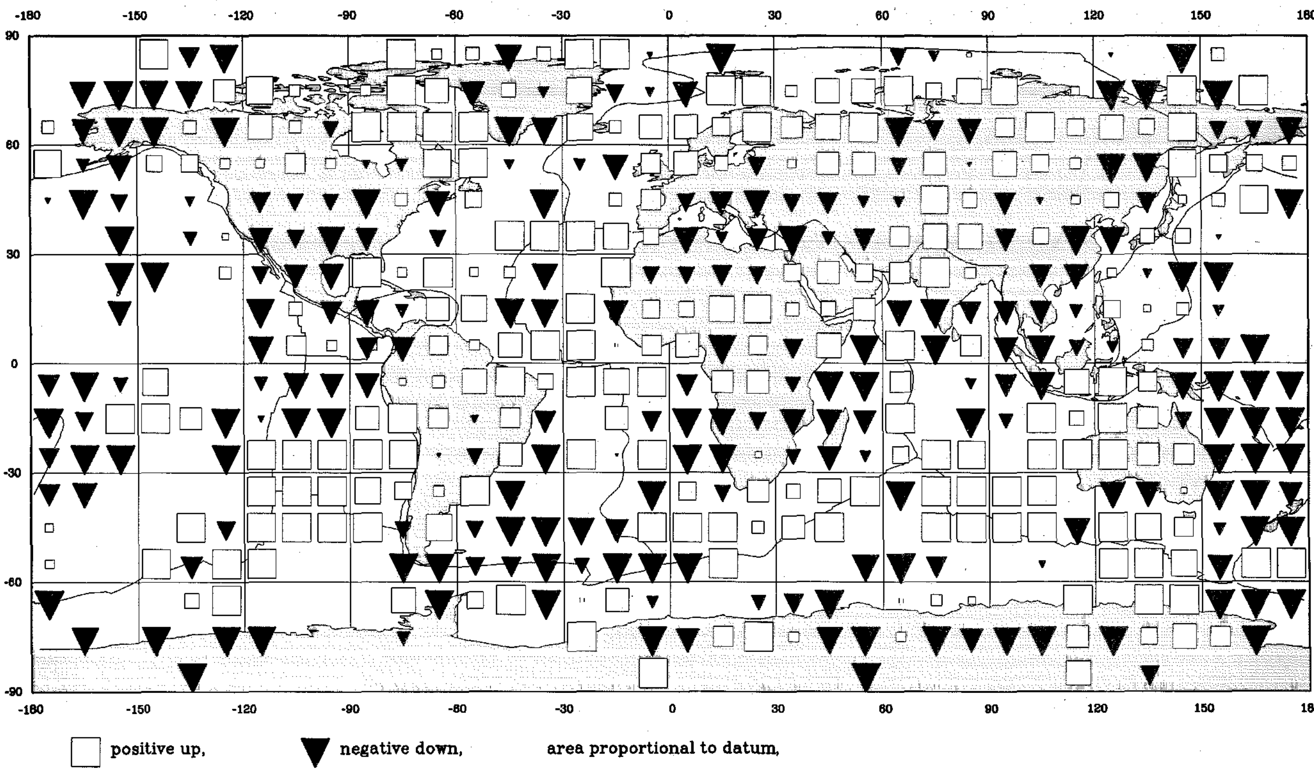
In this kind of illustration the boundaries between the layers always look perfectly smooth, but Caltech researchers have now shown that at least one of those boundaries — the one between the mantle and the outer core — is pockmarked by numerous highs and lows. These underground equivalents of mountains and valleys are thought to result from convection patterns in the semisolid rock of the mantle. Cold, dense, sinking material in the mantle creates the valleys, while hot, rising material creates the mountains.

Mapping those mountains and valleys was a difficult and laborious procedure performed by graduate student Olafur Gudmundsson, Robert Clayton, associate professor of geophysics, and Don Anderson, professor of geophysics. They used the technique of seismic tomography — a means of imaging the interior of the earth with sound waves that is closely akin to the CT scan, a medical technique that provides images of the interior of the human body using X-rays.

In the CT scan, X-rays sent crisscrossing through the body are sensed by a circular array of detectors. The information from these detectors is integrated by a computer that builds up an image based on the density of the different materials within the body. In seismic tomography, earthquake stations around the globe detect the pressure waves that crisscross the earth after earthquakes that occur naturally.

In their studies of the core-mantle boundary, the researchers made use of data gathered from 25,000 earthquakes worldwide with magnitudes of 4.5 and above on the Richter scale. Such earthquakes produce several different types of pressure waves that can be detected by monitoring stations. P waves, for example, are continually refracted by the mantle as they travel from the source of the quake. Eventually, the P waves return to the surface and are detected at monitoring stations. Stations closer to the source of the earthquake will detect the P waves sooner than ones farther away.

Another type of wave, called a PcP wave, travels down through the mantle and is reflected back up to the surface by the core-mantle boundary. The difference in arrival times between P waves and PcP waves is an indirect



Using data from the pressure waves generated by tens of thousands of earthquakes and refracted by the earth's mantle and its inner and outer core (PKIKP waves), graduate student Olafur Gudmundsson generated this map of the topography of the core-mantle boundary. Black triangles indicate downward deflections in the core ("valleys"), and open squares indicate upward deflections ("mountains").

measure of the depth of the core-mantle boundary at a specific point. By comparing the difference in time that's actually measured with the time difference that would be predicted if a smooth core-mantle boundary is assumed, the researchers can build up a map of mountains and valleys. All other things being equal, shorter-than-predicted time differences indicate a mountain and longer-than-predicted time differences indicate a valley.

Unfortunately, all other things are *not* equal. In order to make sense of the data, the researchers must correct for a number of possible sources of error. At the most basic level, they must take into account the fact that the earth is an ellipsoid, not a sphere. But perhaps the most critical corrections involve subtracting known heterogeneities (variations in density) within the mantle as well as variations in the local structure of the earth at the sources of the earthquakes and the sites of the detectors.

Because these correction factors are fraught with many potential sources of error, this new map is of fairly low resolution and contains little detailed information on the exact amplitudes of the deflections at the core-mantle boundary. But it does indicate that the core-mantle boundary contains mountains with heights measured in kilometers under Australia, the Labrador Sea, and off the Pacific coast of South America. There are valleys of similar depths under the southwest Pacific, the East Indies, and southern Europe.

In trying to improve the quality of their maps, the researchers are pursuing two strategies. First, they are continually refining their reference models as details of heterogeneities within the mantle become better known. Second, they're adding measurements from other kinds of waves. PKP waves, for example, pass through the outer core before they are eventually refracted back up to the surface. They provide a nice check on the PcP data since the differences in travel time are reversed. For example, a mountain, which would cause a *decrease* in PcP travel time, will cause an *increase* in PKP travel time.

But PKP waves have a problem of their own: They can be difficult to distinguish from some other waves. To get around this, the researchers are beginning to study PKIKP waves, which pass through the inner as well as the outer core and which can be identified unambiguously. However, the heterogeneities of the inner and outer core are understood in even less detail than the heterogeneities of the mantle.

Despite the difficulties inherent in these seismic tomography studies, the existence of highs and lows on the core-mantle boundary seems to have been corroborated by a separate study of a long-known jerkiness in the earth's rotation. The length of the earth's day varies by about five milliseconds over a decade, and this can be explained by the torque produced as the molten nickel-iron of the core sloshes against the ridges and valley walls at the core-mantle boundary. (This study was conducted by Mary Ann Spieth of Caltech's JPL, Raymond Hide of England's Geophysical Fluid Dynamics Laboratory, Robert Clayton and Bradford Hager of Caltech, and Court Voorhies of the Goddard Space Flight Center.) This study seems to indicate, however, that Gudmundsson and his colleagues may have overestimated the amplitudes of the mountains and valleys. Studies intended to resolve these discrepancies are now under way. □ — *RF*