Continental Drift Nearing Certain Detection

Geodesists are increasingly confident that they are directly measuring the drifting of continents near rates seen in the geologic record

No one is ready to put in print that they have measured how far the continents drifted during the past few years. Such a direct confirmation of the theory of plate tectonics will have to wait a bit longer. But the latest results from space-based measuring systems and a clearer understanding of measurement errors have brought researchers to the brink of claiming a real detection of continental drift.

"A picture seems to be forming in which we see things moving," says Thomas Herring of the Harvard-Smithsonian Center for Astrophysics. He is not yet completely certain, but "the indications are that there is an 80 to 90 percent probability that we're seeing the motion predicted from the geologic record." Herring's colleagues in intercontinental distance measuring agree. Douglas Robertson of the National Geodetic Survey (NGS) in Rockville, Maryland, believes that if the measured motion "isn't significant now, it's very close. We're rapidly approaching the point where we will have a great deal of confidence in the results."

The hesitancy about making any absolute claims persists despite the availability of stunningly precise distance measuring techniques: the problems come from sources of error external to the technology. For example, the method of Very Long Baseline Interferometry or VLBI could measure the distance between Europe and North America with a precision of 3 millimeters, which would reveal the expected 1.7 centimeters per year motion quite promptly, if only Earth had no atmosphere to interfere. Instead, a VLBI measurement across the Atlantic has a precision of only 2 or 3 centimeters, which will require some years of observations for a reliable detection of continental drift.

A greater understanding of this atmospheric interference and other external effects is a major contributor to researchers' increasing confidence. The atmosphere affects VLBI measurements because they depend on radio signals transmitted through the atmosphere. In the course of a VLBI experiment, dish antennas on opposite sides of the Atlantic record radio signals from the same quasar, an extremely distant and therefore stationary reference point. Also recorded is the signal's times of arrival according to each receiver's atomic clock. The differences in arrival times, a few milliseconds at most, for at least three quasars can determine the distance between any two receivers.

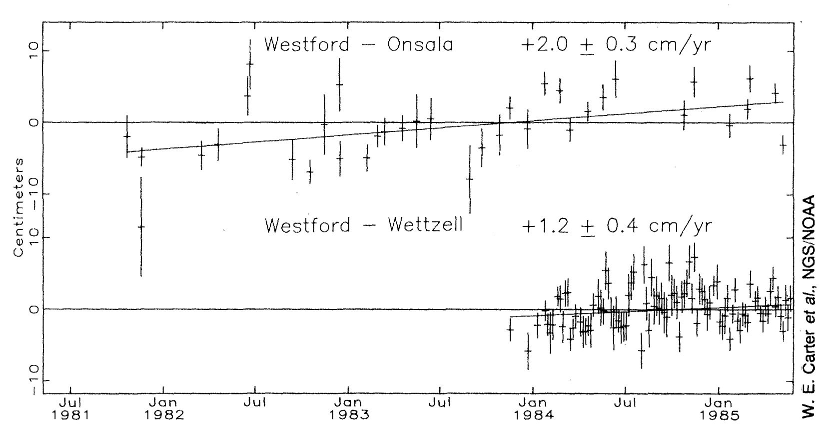
The atmospheric problem arises after the quasar signals have completed all but a millisecond or so of their 10- to 15-billion-year trip. First the ionosphere slows and bends the signal as it follows different paths to different receivers. That distortion has been accounted for by recording the effects on signals at two different wavelengths. Then the signal enters the lower atmosphere, where the signal also slows, but here the effect does not vary with wavelength. The alternative has been to compute the effect of the lower atmosphere from the temperature, pressure, and humidity at the receivers, a crude but helpful means of reducing the observational noise created by the complexities of the atmosphere.

Another subtle but significant source of error is the infinitesimal unsteadiness of Earth. Among a number of irregularities in the rotation of Earth caused by the gravitational pull of the sun and moon is an elliptical squiggle of a few thousandths of a degree traced by Earth's rotation axis every 18.6 years. This nutational motion can influence the apparent length of a baseline. The usual practice has been to use a nutational correction calculated from a mathematical model of Earth's motions under the influence of solar and lunar gravity.

William Carter and Douglas Robertson of NGS have incorporated these and other corrections in their analysis of a VLBI baseline measured monthly during the past 4 years between Westford, Massachusetts, and Onsala, Sweden (*1*). These observations were made primarily to monitor Earth's rotation. The 5600-kilometer Westford-Onsala baseline now appears to be lengthening by 2.0 centimeters per year (*2*), which is invitingly close to the 1.7 centimeters per year deduced from the geologic record of mid-ocean ridge spreading that is magnetically imprinted in the sea floor.

The reliability of such a detection of motion is at the heart of researchers' hesitancy. The rate of 2.0 centimeters per year has a formal error assigned to it of ±0.3 centimeter per year, which is a measure of how much the distance determinations scatter about the best straight line through them. No one believes that the true error is that small. The inability to beat the precision down to a few millimeters using more than 100 observations per day every 5 days shows that systematic errors exist that do not contribute to the scatter of the observations. Presumably these errors lie in the imperfectly modeled atmospheric and nutational effects.

New, less imperfect accounting for systematic error is encouraging researchers to believe that there is something to this apparent opening of the Atlantic. A consortium of researchers



Massachusetts and Europe drifting apart?

These VLBI measurements of the distance between Massachusetts (Westford) and Europe (Sweden, at top, and West Germany) strongly suggest that continental drift is being measured.

from one European and six U.S. institutions, informally known as the East Coast VLBI group, has analyzed data from two transatlantic baselines (*3*). They developed a new, more sophisticated atmospheric model that seems to be an improvement over the old model, especially for sources near the horizon. They also adjusted for nutation using the actual motion as determined by the VLBI observations themselves rather than that predicted by the standard model. Using these improvements, the lengthening of the Westford-Onsala baseline was found to be 3.2 ± 0.6 centimeters per year. That was "marginally significant," according to the group, in light of the inevitably larger systematic error.

The East Coast group has since made another improvement, according to Herring. Instead of subjectively sorting out nanosecond variations in each site's atomic clocks, they now use a more objective method involving Kalman filtering. Using this method and including the eight most recent distance determinations on the Westford-Onsala baseline, they find a rate of 2.3 ± 0.3 centimeters per year. Because the primary interest in experiments at the Westford observatory has been Earth's rotation, the East Coast group considers the best determined baseline to be between the neighboring Haystack Observatory antenna, which is larger and more sensitive, and Onsala. Four years of these observations have been made as part of the Crustal Dynamics Project. The group's latest and best analysis of that data yields a rate of 2.0 ± 0.2 centimeters per year, which is the same rate as their analysis of the Westford-Onsala baseline.

A growing consensus that the true error in these measurements is about 1 centimeter per year supports privately held opinions that the detection of continental drift is imminent if not already accomplished. How best to estimate true error is as much a philosophical as a technical question, but three approaches—those of NGS, the East Coast group, and a West Coast group centered at the Jet Propulsion Laboratory—seem to be converging on the same 1 centimeter per year figure as a reasonable error estimate for the best VLBI data. The major remaining area for improvement seems to be further verification of the new atmospheric model and, within a few years, the routine use of radiometers to infer the amount of water vapor along the radio signal's path.

Additional confidence has been engendered by the preliminary results from

An Agenda for Space Physics

The National Academy of Science's Committee on Solar and Space Physics, representing the researchers who study the sun, the solar wind, the upper atmosphere, and the magnetospheres of Earth and the other planets, has released its recommendations for a 20-year program of federally supported space missions.*

The space physicists have thus followed in the footsteps of the astronomers in the Academy's Field Committee and the planetary scientists in the National Aeronautics and Space Administration's (NASA's) Solar System Exploration Committee. However, it remains to be seen whether their report will be as influential as their predecessors'. Produced by a 15-member panel chaired by Stamatios M. Krimigis of The Johns Hopkins University, it calls for a 30 percent boost in the program's annual budget at a time when the federal government as a whole is facing huge deficits, and when the NASA space science office in particular is trying to divide its budgetary pie among more and more disciplines. On the other hand, the report may well prove effective as public relations: it dramatizes the solar/space physics program at a time when its two highest priority missions have fallen into budgetary limbo.

The first of these missions is the Solar Optical Telescope (SOT), a high-resolution instrument scheduled to fly on the space shuttle in the early 1990's. SOT has been delayed repeatedly as NASA focused its money and attention on completing the Hubble Space Telescope. This year, a deficit-minded Congress has slashed the SOT budget yet again, leaving the fiscal year 1986 funding uncertain. Some researchers are concerned that another year of severe underfunding might lead NASA to abandon the project.

The second troubled priority is the International Solar Terrestrial Physics mission, which addresses the interaction of the solar wind with the magnetosphere of the earth. According to agreements signed in 1983, the mission will involve six satellites: three from the United States, two from the European Space Agency, and one from Japan. However, budgetary constraints have forced NASA to delay this project also. Agency officials still hope for funding in fiscal year 1987. But the Japanese are reportedly getting restive; any further delay may lead them to drop their portion of the project entirely. Meanwhile, there is some chance that the Europeans will go ahead with their two spacecraft on their own—thereby undermining one of the most valuable aspects of the mission, the simultaneous collection of data from multiple points in the magnetosphere.

The other two major missions recommended by the committee are less problematic simply because they are much further off. The Solar Probe, targeted for launch in 1995, would fly to within 2.5 million kilometers of the solar surface to explore the origins of the solar wind. The Solar Polar Orbiter, targeted for launch in 2000, would orbit over the poles of the sun to explore the three dimensional properties of the heliosphere.

Rounding out the recommended package is a series of moderate-sized missions. These would include free-flying explorer-class satellites, to be launched at the rate of about one per year, plus a continued program of experiments aboard the shuttle, and eventually aboard the space station.

Altogether, the report calls on NASA to boost its funding for solar and space physics from its current $300 million per year to roughly $400 million per year. However, while there will definitely be a rise if and when the solar-terrestrial mission is approved, say NASA officials, it is not at all clear that NASA will be able to keep the funding at that level afterward. Indeed, one sore point for researchers is that in 1980, after a series of personality clashes and turf battles within NASA, the solar/space physics program was broken up among four different jurisdictions. The upshot is that the community has no single, high-level voice in arguing for new missions. The committee has suggested that the program be reassembled into a new office of its own. But it is anyone's guess whether NASA will do so.

—**M. MITCHELL WALDROP**

***An Implementation Plan for Priorities in Solar-System Space Physics* (National Academy Press, Washington, D.C., 1985).

satellite laser ranging under the Crustal Dynamics Project. In SLR the time required for a laser burst's roundtrip between the ground and a reflector-equipped satellite is used to determine the site's location. The errors in SLR are generally thought to be larger and more poorly understood than in VLBI, due in part to the use of a single satellite, decimeter errors in estimates of the position of the satellite, and the nonsimultaneity of observations. But what SLR lacks in precision it at least partially makes up for by the large number of sites in operation and the ability to determine distances between all sites in the network.

Demos Christodoulidis of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and his colleagues report that five of six observed average plate motions determined between the North American, Pacific, and Australian plates are in general agreement with the geologic rates (*4*). One of the most clear-cut agreements is in a closing rate averaged from four lines between the Australian and Pacific plates of 4.6 ± 0.9 centimeters per year versus the geologic rate of 6.0 centimeters per year. The best SLR determination of plate motion comes from Southern California where the observed rate of motion between the North American and Pacific plates along the San Andreas fault is 6.1 ± 2.5 centimeters per year versus the geologic rate of 5.8 centimeters per year.

Once geodesists are quite sure that they are detecting real motion, they will be comparing it with geologic rates, which are averaged over at least 100,000 years. Then they will collect rates between and within as many plates as possible in order to pin down the modern forces that now jostle the plates, build mountains, and trigger earthquakes.

—RICHARD A. KERR

References

1. W. E. Carter, D. S. Robertson, J. R. MacKay, *J. Geophys. Res.* **90**, 4577 (1985).
2. W. E. Carter, D. S. Robertson, T. E. Pyle, J. Diamante, paper presented at the IAMAP/IAPSO Joint Assembly, Honolulu, Hawaii, 7–8 August 1985.
3. T. A. Herring *et al.*, *J. Geophys. Res.* (submitted).
4. D. C. Christodoulidis *et al.*, *ibid.*, in press.

WIMP's, Cosmions, and Solar Neutrinos

The same mysterious particles that dominate the evolution of the universe may also lurk in the core of the sun

The same weakly interacting, massive particles—WIMP's—that are thought to comprise the mysterious dark matter in the universe, and that perhaps triggered the formation of the galaxies (*1*), now seem to offer an elegant explanation for the solar neutrino problem.

Nearly two decades old, the solar neutrino problem rests on a sharp contradiction between theory and experiment. On the one hand, the standard astrophysical models of the sun predict that nuclear reactions in the core will release swarms of neutrinos at a certain, calculable rate. These neutrinos will then stream freely through the sun's outer layers and, in principle, will be detectable on the earth. On the other hand, a solar neutrino detector developed by Brookhaven National Laboratory's Raymond Davis has operated since 1968 in South Dakota's Homestake gold mine and has consistently measured a neutrino flux only one-third of the predicted value.

Over the years this neutrino deficit has become a major embarrassment for the theorists. Their standard model of the sun is based on well-understood nuclear physics, and has been very successful in relating the mass and composition of the sun to its luminosity and lifetime. So almost anything they do to damp out the neutrino production has to leave those predictions unchanged, which turns out to be extremely difficult. Indeed, their struggles have led them down some bizarre pathways. One hypothesis has it that a black hole has fallen into the center of the sun and will eventually cause the sun to collapse on itself. Another says that the sun has somehow turned off inside, and that the outer parts are only just beginning to cool.

Thus the appeal of WIMP's: they suppress the solar neutrinos without substantially altering the standard models of the sun.

The key idea was actually first noted in 1978 by astrophysicist John Faulkner of the University of California, Santa Cruz, and his graduate student Ronald Gilliland, now at the National Center for Atmospheric Research in Boulder, Colorado. They started from the fact that the Homestake detector is sensitive only to relatively high energy neutrinos produced by a certain rare reaction involving boron-8. This reaction in turn is very sensitive to temperature, so that the neutrino production tends to be highly concentrated at the center of the sun where temperatures reach their peak. In fact, in the standard solar models roughly 70 percent of the detectable neutrinos are produced within the central 5 percent of the radius, whereas less than 10 percent of the sun's luminosity is produced there.

Faulkner and Gilliland's idea was thus to postulate a haze of WIMP's orbiting almost freely in the core of the sun. In particular they were thinking of massive neutrinos left over from the big bang, which were then quite fashionable in cosmological circles. But in any case, if these hypothetical particles had the right mass—roughly 5 GeV—and if they interacted often enough with the ordinary nuclei—say, once every orbit or so—they could pick up energy at the center and distribute it throughout the core, thereby smearing out the temperature peak and damping the solar neutrino production *without* having any significant effect on the luminosity. Indeed, Faulkner and Gilliland's calculations showed that the energy transport would be quite efficient, so that only a relatively small number of WIMP's would be needed.

Unfortunately, big bang neutrinos in the 5 GeV mass range seemed to be ruled out from other cosmological evidence. Thus, unwilling to add to the list of "obviously crazy" solutions to the solar neutrino problem, Faulkner and Gilliland let the idea go by with only a brief mention in another paper (*2*).

Recently, however, the idea has been revived quite independently by William H. Press and David N. Spergel of the Harvard-Smithsonian Center for Astrophysics, who were inspired by the increasingly strong evidence that WIMP's play a major role in cosmic evolution, and by the plethora of new WIMP candidates being hypothesized by the particle physicists (*3*). (Actually, Press and Spergel prefer the name "cosmions".) In the process, the Harvard researchers have also pointed out a natural mechanism for getting the cosmions into the sun. As-