Bill Johnson shows off a prototype putter whose head is one solid piece of metallic glass. The pizza paddle behind him is actually the biggest chunk of metallic glass ever cast, and is typical of the ingots from which the club-face inserts are cut.

Random Walk

FORE!

Tiger Woods doesn't really need them, and the average duffer probably can't afford them, but a new set of golf clubs that can easily add ten yards or more to your drive is coming on the market. The reason you're reading about them in *Engineering & Science* instead of *Golf Digest* (where they'll appear next month) is that these clubs have a face, or striking surface, made of a metallic glass developed by Caltech researchers and trade named Liquidmetal. This stuff is perfectly elastic, says William Johnson (PhD '75), the Mettler Professor of Engineering and Applied Science. To prove it, he drops a ball bearing on a titanium plate—the high-tech metal of choice for golf-club heads. The bearing bounces perhaps a dozen times. When the demonstration is repeated with a Liquidmetal plate, the bearing bounces like a Superball.

"When the liquid becomes complicated enough, it can't figure out how to crystallize because there aren't any nice, simple, orderly patterns it can settle into, and while it's thinking about it, we can cool it enough to solidify it."

Ordinary metals are crystalline—as the melt cools, the atoms snuggle together in neat, orderly arrays. When you apply stress to the metal—by hitting a golf ball with it, for example—one plane of atoms slips partially out of alignment with the neighboring plane, creating the equivalent of a wrinkle in a rug. These dislocation defects, as they're called, absorb energy that would otherwise be imparted to the ball. (Ultimately, of course, if you put enough stress on the metal the slippage leads to metal fatigue and fractures.) So if you could get rid of the crystalline structure, you'd get a much stronger, more flexible metal that can take high stresses without absorbing energy. (You'd get other interesting properties as well—see *E&S*, Winter 1990.)

Metallic glasses, however, are amorphous, not crystalline. Like a big paper bag stuffed full of golf balls, the atoms are loosely jumbled, with no regular pattern to their arrangement—no neat arrays. A glass is really just a very cold liquid in that respect, but an extremely viscous one—the atoms are packed so densely that they aren't free to move or flow.

Amorphous metal ribbons less than a tenth of a millimeter thick have been on the market since 1973, but that's all that has been available until now. Ordinary metals crystallize so incredibly rapidly that bypassing the process means cooling the melt by a million degrees per second or more, which can only be done with very thin layers of metal. And the cooling has to be rigorously uniform throughout the piece—a few scattered crystals in the interior of the material, and it becomes as brittle as a common ceramic. Try teeing off with a porcelain golf club!

In order to make chunks instead of ribbons, you'd have to figure out how to cool the melt at a more reasonable rate—a few degrees per second, say—while still forestalling crystallization. Atakan Peker (PhD '94) did just that in his thesis, says Johnson. "He realized that we had to go to a very complicated material. We need to have four or more atoms with different chemical characteristics before the liquid gets sufficiently frustrated in its efforts to crystallize. When the liquid becomes complicated enough, it can't figure out how to crystallize because there aren't any nice, simple, orderly patterns it can settle into, and while it's thinking about it, we can cool it enough to solidify it. We might call this the 'confusion principle.'" Peker used a five-metal mixture of zirconium, titanium, nickel, copper, and beryllium, but even that only glassifies over a very narrow range of compositions.

But why take this marvelous material and make golf clubs? Well, you've got to start somewhere. And, says Johnson, "golf is a very demanding application. When a good golfer hits the ball, the club head is moving at 100–110 miles per hour, and you do this thousands of times over the life of the club." Casting a club head is no stroll down the fairway, either—drivers are hollow, irons are concave in back, and even the simple slab of the humble putter is problematical. The trouble is that the metallic-glass-forming melt is a hundred to a thousand times more viscous than an ordinary molten metal alloy. "It's more like a thermosetting polymer," says Johnson. "It doesn't flow very well. Bubbles don't float; debris doesn't sink." David Lee (PhD '94) and Michael Tenhover (MS '78, PhD '81) had to develop an entirely new set of manufacturing techniques to work with the stuff.

So the first clubs have a 2.5- to 3-millimeter-thick amorphous insert for the striking face, bonded to a steel or titanium club head. They recently went on sale in Japan, where golf is really big and folks are willing to pay top dollar for the latest technological wrinkle. (It made sense to start selling them there first, says Johnson, in order to cover the new technology's startup costs.) But now Amorphous Technologies International, the Laguna Niguel company where Peker et al. now work, is gearing up to start production of fully amorphous club heads here in the United States. If they meet their goal of having a set of irons on the market by April, 1998, says Johnson, it will set some sort of record for moving a material from a laboratory curiosity to a consumer product. And the lessons learned while making golf clubs can be applied not only to other sporting goods such as tennis rackets, baseball bats, and bicycle frames, but to such demanding applications as jet-engine compressor blades and medical prostheses. ☐—*DS*

GOOD NEWS AND BAD NEWS FOR MARTIAN MARINERS

The good news is that Mars Global Surveyor, which slid into orbit around the red planet on September 11, has discovered a Martian magnetic field. (Previous, more distant observations by several spacecraft had been inconclusive.) The bad news is, you can't navigate by it.

The existence of a planetary magnetic field is often seen as a prerequisite for the development and continued existence of life. A strong magnetic field would shield a planet from the fast-moving, electrically charged particles of the solar wind that would otherwise bombard the upper atmosphere, breaking water and other molecules down into ions that then escape into space. So a strong magnetic field helps a planet keep its atmosphere, and with a dense enough, warm enough atmosphere, Mars could have had liquid water on its surface. The field would also intercept cell-damaging cosmic rays that would otherwise penetrate to the surface.

Planets like Earth, Jupiter, and Saturn generate their magnetic fields by means of a dynamo made up of moving molten metal at the core. This metal is a very good conductor of electricity, and the rotation of the planet creates electrical currents deep within the planet that give rise to the magnetic field. (Mars presumably used to have a molten interior, too, since huge, dead volcanoes dot the planet's surface.)

But that dynamo is no longer turning fast enough to sustain a single, global field, because Mars Global Surveyor's magnetometer swung wildly as the spacecraft buzzed the planet. In some places the field is pointing straight up; in others, straight down; and in still other places the field lies parallel to the surface. This indicates that the field is a fossil frozen into the rocks of the crust, and that it has splintered and rotated with the rocks carrying it. If the patchwork could be reconstructed, it would tell scientists a lot about the planet's geological history. The strongest patches were 40 times the strength of comparable regions on Earth, so the Martian field must once have been quite substantial.

The spacecraft discovered the outermost boundary of the Martian magnetic field—known as the bow shock—during the inbound leg of its second orbit around the planet, and again on the outbound leg. The discovery came just before Mars Global Surveyor began its first aerobraking maneuver, in which the spacecraft dips into the upper fringes of the Martian atmosphere, allowing the drag on its solar panels to slow it down and eventually plop it into the circular orbit from which it will map the planet. It will continue aerobraking through the Martian atmosphere for the next four months, until it is flying about 378 kilometers above the Martian surface.

Additional information is available at several World Wide Web sites, including the JPL home page at http://www.jpl.nasa.gov/marsnews, the Mars Global Surveyor home page at http://marsweb.jpl.nasa.gov, and the Goddard Space Flight Center magnetometer site at http://mgs-mager.gsfc.nasa.gov.

The Mars Global Surveyor is managed by the Jet Propulsion Laboratory, which Caltech manages for NASA. JPL's industrial partner is Lockheed Martin Astronautics, in Denver, Colorado, which developed and operates the spacecraft. ☐

ACE IS HIGH

NASA's Advanced Composition Explorer (ACE), which lifted off on August 25, carries two Caltech instruments. ACE is headed for an orbit around the point between Earth and the sun where the gravitational and centrifugal pulls balance. Once there, it will sample the not-so-empty space of our solar system. The atoms and ions whizzing around out there come from three sources: the sun, the local interstellar medium, and the Great Beyond. Each particle has a tale to tell about when and where it was born, and where it's been since.

ACE's nine instruments will count the particles, measure their kinetic energies and ionization states, and even discriminate between different isotopes of every chemical element from helium to zinc. Between them, the instruments cover a millionfold range of particle energies with a sensitivity 10–1,000 times better than previous missions. The two Caltech instruments—the Cosmic Ray Isotope Spectrometer and the Solar Isotope Spectrometer—were built in the Space Radiation Lab by teams headed by Senior Research Associate in Physics Richard Mewaldt and Member of the Professional Staff Alan Cummings (PhD '73), in collaboration with researchers from JPL, NASA/Goddard, and Washington University. Caltech also had overall responsibility for the other instruments. (The spacecraft itself was built by Johns Hopkins University's Applied Physics Lab.)

Parked as it will be between us and the sun, it is probably not surprising that the sun looms large on ACE's agenda. The solar wind and other, higher-energy particles, both of which come from the sun's outer layers, are the only solar matter that humans can analyze directly, says Mewaldt. The relative abundances of various isotopes in those particles, which ACE can measure and cameras and spectrographs can't, will tell us more about what matter in the universe was like when the sun condensed, 4.6 billion years ago. And instruments that measure the charge on individual particles will take the temperature of the region of the sun that the particles came from—hotter layers strip off more electrons from the ions they emit. ACE will also study the sun's enormous magnetic field, and as a side benefit will provide about one hour's warning of the powerful magnetic storms that can black out power grids, disrupt communications, and even fry satellites.

Moving up the energy spectrum are the so-called "anomalous cosmic rays," which are atomic nuclei from the interstellar medium—the thin, thin gas that lies beyond the boundaries of our solar system. As stars age, they create elements heavier than helium in their bowels. When they die, some of this material is ejected into the interstellar medium for future stars to condense from. Thus the matter from which tomorrow's stars will be born is not what it was when the sun was conceived; ACE will tell us how it has changed.

And finally, the most energetic particles ACE can detect are the galactic cosmic rays, which come from within our galaxy but may have traversed it many times, trapped in its magnetic field, before blundering into our solar system. Their exact origin is still a mystery, which ACE should help resolve, but the relative abundances of radioactive isotopes in them (the same principle as carbon-14 dating) shows that, on average, they are 10–20 million years old, says Cummings. They thus constitute a sample of galactic matter of intermediate age.

ACE entered its design phase in 1991, just in time to be a guinea pig for NASA's "faster, better, cheaper" mandate. "We had a cost cap and a fixed launch date," Cummings recalls. "Miraculously, we hit our launch window, and even had some $30 million left to give back to the agency." He credits close cooperation with JPL, which provided technical support and experienced personnel to help keep track of the instruments that Caltech wasn't building. (It probably didn't hurt that Ed Stone, director of JPL and vice president of Caltech, is ACE's principal investigator.) "It's a model for how the Explorer program can run in the future." ☐—*DS*

SEE MARS IN 3-D; HEAR IT IN STEREO

Dramatic 3-D pictures from JPL's Mars Pathfinder mission will be shown during a performance of Gustav Holst's "Mars" at the season's first Caltech-Occidental Concert Band performance, conducted by William Bing, who has purchased 600 sets of 3-D glasses for the occasion. The pictures come courtesy of Robert Manning (BS '82), a trumpet player with the Caltech Jazz Band and Pathfinder's chief engineer. The concert begins at 8 p.m. Saturday, November 15, in Caltech's Beckman Auditorium. The concert is free and open to the public, with seating available on a "first come" basis.

In addition to the performance of "Mars" from Holst's suite *The Planets*, the program will include music by George Gershwin and excerpts from the musical *Ragtime*. Guest conductor Daniel Kessner will conduct one of his own compositions, which was recently commissioned by a consortium of colleges, including Caltech.

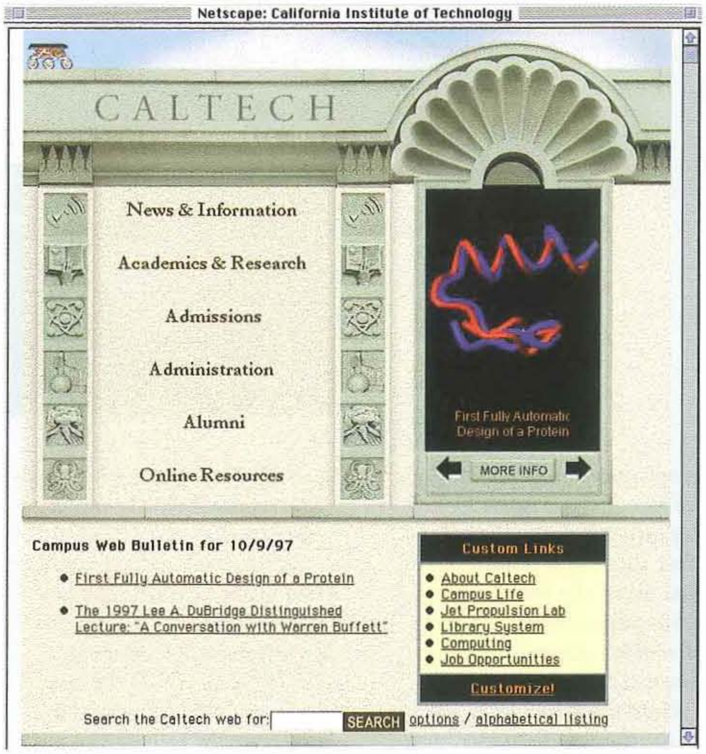
Fall Watson Lectures Set

This year marks the 75th anniversary of the Earnest C. Watson Lectures, a series that has not only grown up with the Institute, but literally shaped it: Beckman Auditorium was designed in part with these public lectures in mind. On October 29, David and Judith Goodstein will present "Earnest Watson and the Amazing Liquid Air Show" in homage to that first talk in 1919.

Then, on November 5, in "Gamma-Ray Bursts: Dying Cries from the Deep Universe," Professor of Astronomy and Planetary Science Shrinivas Kulkarni will describe astronomers' search for the source of these bursts, and present their surprising conclusions.

In "Touching Mars," on November 19, Donna Shirley, manager of JPL's Mars Exploration Program, will discuss the ambitious slate of one Mars mission every 26 months through about 2015 that began with the Pathfinder and Mars Global Surveyor.

And in "The World of Our Grandchildren: Visualizing Alternative Futures with the World Wide Web," on January 14, 1998, Professor of Planetary Science and Geology Bruce Murray will talk about the "Hyperforum," an experiment in discourse that uses the World Wide Web to analyze complex problems such as the long-term sustainability of global development.



Campus Web Bulletin for 10/9/97

- First Fully Automatic Design of a Protein
- The 1997 Lee A. DuBridge Distinguished Lecture: "A Conversation with Warren Buffett"

Caltech's homepage, http://www.caltech.edu, has a new look. Designed by Aurelius Prochazka (PhD '97) and colleagues Jacob Mandelson, Danny Petrovich, and Athina Peiu Quake (wife of Assistant Professor of Applied Physics Stephen Quake), the Web site was commissioned by Provost Steve Koonin and the Web Executive Council. Members of the council would appreciate feedback on the new site. For a list of members and their e-mail addresses, visit http://caltech/subpages/credits.html; or e-mail the council directly at web@cco.caltech.edu.

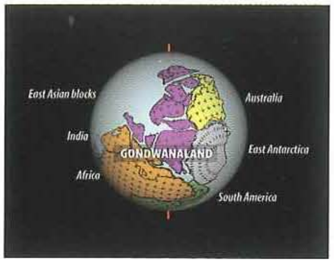
Cassini Launched at Last

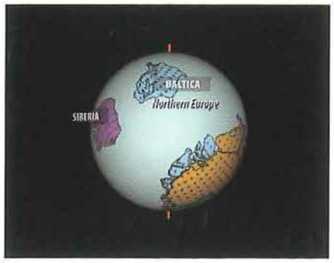
In other news from the Cape, JPL's Cassini mission to Saturn was finally launched at 4:43 a.m. Eastern Daylight Time on October 15, after numerous delays. The spacecraft will get gravity-assisted boosts from Venus (twice), Earth, and Jupiter en route, and is slated to arrive at the ringed planet in July 2004. Once there, it will spend four years studying the Saturnian system much as Galileo is doing at Jupiter. Cassini even has a probe of its own—the European Space Agency's Huygens, which will parachute into the nitrogen-rich atmosphere of Titan, Saturn's largest moon. If the probe survives the landing, it will study Titan's hydrocarbon-rich surface, which in some ways may resemble that of the prebiotic Earth.

Atlas Shrugged

Caltech researchers think they have solved part of the mystery of the "evolutionary big bang" that occurred half a billion years ago. At that time, life on Earth underwent a profound diversification that saw the first appearance in the fossil record of virtually all animal phyla living today. With relative evolutionary rates of more than 20 times normal, nothing like it has occurred since. In a paper published in the July 25th issue of *Science*, the Caltech group reports that this evolutionary burst coincides with another apparently unique event in Earth history—a 90-degree change in the direction of Earth's spin axis relative to the continents. Professor of Geobiology Joseph Kirschvink (BS, MS '75), lead author of the study, speculates that a major reorganization of tectonic plates during the late Precambrian changed the balance of mass within the Earth, triggering the reorientation. Thus, the regions that were previously at the north and south poles were relocated to the equator, and two antipodal (or opposite) points near the equator became the new poles.

"Life diversified like crazy about half a billion years ago," says Kirschvink, "and nobody really knows why. It began about 530 million years ago, and was over about 15 million years later. It is one of the outstanding mysteries of the biosphere. The





Above are three views of how Earth's continents were arranged about 530 million years ago. The red posts are Earth's spin axis; the colors are keyed to today's continents. (India is under the "wana" in "Gondwanaland.") Most of the continental mass is concentrated around the south pole (which is projecting outward in the middle picture), a rotationally unstable situation. The planet compensates by shifting its axis until the excess mass is centered on the equator, as shown in the sequence of pictures above right. (Although the axis moves with respect to the continents, as shown here, it remains fixed with respect to the plane of the solar system.)

geophysical evidence that we've collected from rocks deposited before, during, and after this event demonstrate that all of the major continents experienced a burst of motion during the same interval of time."

Grad student David Evans, a coauthor of the paper, notes that it is very difficult to make large continents travel at speeds exceeding several feet per year; typical rates today are only a few inches per year.

"Earth has followed a 'plate-tectonic speed limit' for the past 200 million years or so, with nothing approaching the rates needed for this early Cambrian reorganization," Evans said. "Some other tectonic process must have been operating that would not require the continents to slide so rapidly over the upper part of Earth's mantle."

In fact, geophysicists have known for over half a century that the solid, elastic part of a planet can move rapidly with respect to its spin axis via a process known as "true polar wander." True polar wander, Kirschvink explains, is not the same as the more familiar plate motion that is responsible for earthquakes and volcanism. While the latter is driven by heat convection in Earth's mantle, true polar wander is caused by an imbalance in the mass distribution of the planet itself, which the laws of physics force to equalize in comparatively rapid time scales.

During this redistribution, the entire solid part of the planet moves as a unit, avoiding the internal shearing effects that impose the speed limit on conventional plate motions. (While this is happening, of course, Earth maintains its original spin axis in relation to the plane of the solar system.) Thus, true polar wander can result in land masses moving at rates hundreds of times faster than tectonic motion caused by convection.

An analogy of the effect can be seen by cementing lead weights at antipodal points on a basketball. If the ball is then set on a slick floor and spun with the weights along the equator, the ball will spin in the manner one would normally expect, with the weights remaining on the equator. If the ball is spun on one of the lead weights, however, the axis of rotation will tend to migrate until the weights are again on the ball's equator. This way, the spinning ball has aligned its maximum moment of inertia with the spin axis, as required by the laws of physics.

As for astronomical evidence that such a phenomenon can occur, the authors point to Mars. Along the equator of the red planet is a gigantic volcano called Tharsis, which is known to be the largest gravity anomaly in the solar system. Tharsis could have formed on the equator, but more likely formed elsewhere on the planet and then migrated to the equator via true polar wander because of rotational torques on its excess mass.

Something similar must have happened to Earth, says Kirschvink. At about 550 million years ago, 20 million years before the evolutionary burst, one or more of the chief subduction zones in the ancient oceans closed down during the final stages of assembly of the supercontinent of Gondwanaland, leading to a major reorganization of plate-tectonic boundaries.

Geophysicists have known for many years that this type of reorganization could, in theory, yield a sharp burst of true polar wander. In particular, if Earth were slightly "football shaped," with a major, stable mass anomaly on the equator and a more equal distribution of mass elsewhere, only slight changes of the smaller masses would be needed to produce large motions. A burst of motion up to 90 degrees in magnitude could even be generated if the maximum moment of inertia (about which the planet spins) became less than the intermediate moment (which is always on the equator). The massive plate motions observed by the Kirschvink group fit the predictions of

"A progressive shift of this magnitude could cause oceanic circulation patterns to become rather unpredictable, jumping from one semi-stable configuration to another on a million-year time scale. Imagine the havoc that would result in Europe if the Gulf Stream were to disappear suddenly."

this "inertial interchange" event rather closely.

Over the 15 million year duration of this true polar wander event, the existing life forms would be forced to cope with rapidly changing climatic conditions as tropical lands slid up to the cold polar regions, and cold lands became warm. "Ocean circulation patterns are sensitive to even slight changes in the location of the continents," says coauthor Robert Ripperdan (MS '85, PhD '90), a geochemist at the University of Puerto Rico. "A progressive shift of this magnitude could cause oceanic circulation patterns to become rather unpredictable, jumping from one semi-stable configuration to another on a million-year time scale. Imagine the havoc that would result in Europe if the Gulf Stream were to disappear suddenly."

These jumps offer an explanation for yet another unique mystery of the Cambrian explosion, which is a series of nearly a dozen large swings in the marine record of carbon isotopes. "Repeated changes in global oceanic circulation patterns should ventilate organic carbon buried in the deep oceans, producing these carbon wiggles," Ripperdan says. "We used to think that they were somehow due to repeated expansion and contraction of the entire biosphere, but no one could think of a mechanism to do that. All of the evidence suddenly makes sense with this true polar wander model."

But what caused the evolutionary burst? Kirschvink notes that these global shifts in oceanic circulation will also act to disrupt regional ecosystems, breaking them down into smaller, more isolated communities. "Evolutionary innovations are much more likely to survive in a small, inbreeding population, rather than in large, freely interbreeding groups," he notes. "And the carbon cycles are telling us that major changes in ocean circulation happened about every million years or so. That is certainly enough time for natural selection to weed through the fragments left by the last disruption, and to form new, regional-scale ecosystems. Then, wham! They're hit again and the process repeats itself. That is a great script for increasing diversity, particularly as it seems to have happened shortly after the evolution of major gene systems that regulate animal development." The upshot was that evolution proceeded nearly 20 times faster than its normal rate, and the life of the planet diversified into many groups still living today.

Kirschvink and his collaborators base their conclusions on data collected from 20 years of work on numerous well-exposed sections of the Precambrian-Cambrian and Cambrian-Ordovician eras. By using ultrasensitive superconducting magnetometers to study the weak fossil magnetism (paleomagnetism) left in many rocks as they formed, the researchers can recover the direction of the ancient geomagnetic field. This points in the vicinity of ancient north, for the same reason that a magnetic compass can be used to find the approximate north direction today.

This remanent magnetism can also provide an estimate of the ancient latitude in which the sediments were deposited, as the inclination (or dip) of the magnetic field changes smoothly with latitude—it points vertically at the poles and is horizontal (tangent to Earth's surface) on the equator. Therefore, the fact that magnetic materials are found pointing in other directions is evidence that the ground itself has moved in relation to Earth's magnetic north, which is locked over time to the spin axis.

Geological samples collected by the Caltech group in Australia (which has some of the best-preserved sediments of this age from all of Gondwanaland) demonstrate that this entire continent rotated counterclockwise by nearly 90 degrees, starting at about 534 million years ago (coincident with the onset of the major radiation event in the Early Cambrian), and finishing sometime during the Middle Cambrian. North America, on the other hand, moved rapidly from its end-of-the-Precambrian position deep in the southern hemisphere, and achieved a position straddling the equator before the beginning of the Middle Cambrian, about 518 million years ago. Even the type of marine rocks deposited on the various continents —carbonates in the tropics, and clays and clastics in the high latitudes—agree with these paleomagnetically determined motions. The paleomagnetic directions are accurate within about 5 degrees, the authors write. Latitudes are quite reliable, but because the poles moved so rapidly, even the relative longitude between blocks can be determined. This true polar wander analysis predicts a unique "absolute" map of the major continental masses during this event, an animation of which can be viewed at http://www.gps.caltech.edu/~devans/iitpw/science.html.

"This hypothesis relating abrupt changes in polar wander to evolutionary innovations could be tested in many ways," notes Kirschvink, "as there are some interesting events in the paleontological record during the following 200 million years which might have been triggered by similar processes. There's lots of work to do." ☐—*RT*