EXPERIMENTAL RELATIVITY:

Advances in space technology, microwave techniques and atomic clocks are opening up the entire solar system as a laboratory for relativity. Scientists may soon be able to uncover the secrets of the sun's interior, tune in the gravitational waves sent out by distant galaxies and measure the shape of space-time itself.

BY MARCIA F. BARTUSIAK


Jet Propulsion Laboratory

An exploratory spacecraft looks down at the fiery solar surface during man's closest venture to the sun. If funded, this solar probe would be launched by NASA *in 1987 and include several relativity experiments as part of the instrumentation package.*

It is the fall of 1992. An unmanned probe whips past the sun at some 300 kilometers per second, several times faster than any previous spacecraft. As the probe passes over the solar poles, it sends back information that will vastly increase our knowledge of how the sun works, just as its cousins Pioneer, Mariner, Viking and Voyager reshaped our understanding of the planets.

Dipole antennas built of high temperature metal search for oscillating electric and magnetic fields within the corona in hopes of finding the mechanisms that heat the corona and drive the solar wind. Special spectrometers measure the sun's energetic particle flux to determine how the particles are created and then released into interplanetary space. At the same time, imaging systems peer down at the sun's surface to watch the solar plasma erupt into large loops and prominences. Their visible, ultraviolet and X-ray "eyes" provide resolutions 5 to 50 times better than earth-orbiting telescopes. As the data collection proceeds, a heat shield remains pointed at the fiery surface to protect much of the delicate instrumentation from the equivalent of 2,500 suns shining down on the earth.

The scenario above describes a proposed mission now on NASA's drawing board — the Solar Probe. If the project receives a monetary go-ahead, it would be man's closest venture to the sun, exploring regions near and even within the solar corona. In the mid 1970s, the German probes Helios A and B approached within 0.3 AU of the sun (1 AU = 150 million kilometers, the average distance between the earth and sun). The solar probe, on the other hand, would have a .02 AU perihelion. NASA likes to describe it as an "encounter with a star."

Because of its wide variety of experiments, the probe would be many things to many fields of science. But perhaps the most excited will be the experts in experimental relativity. By having a space probe approach within two to three million kilometers of the sun's surface, they may be able to solve its greatest mysteries. How is the sun's mass distributed in the deep solar interior? Is it spherical or oblate? Is the core spinning at the same speed as the outer convective layers or more rapidly? And what is the sun's total angular momentum? These are questions that can only be answered by exploring the sun's gravity and relativistic perturbations at very close distances. When it's farther away from the sun, the probe may also be able to tune in the gravitational waves sent out by distant galaxies.

Such activity will be quite a change for relativists. Until recently, general relativity and experimentation were words you didn't often see in the same sentence. For decades, theorists have had the upper hand in working with modern theories of gravity (now nearly synonymous with relativity). With paper and pencil they have sat back at their desks to map out the strange relativistic effects around black holes and to move clocks at near-light speeds around the far reaches of the universe. It's estimated that experimental tests lag behind by as much as half a century. What are the reasons for this? In describing the motion of a ball falling to the ground or a spacecraft orbiting the moon, Newton's Universal Law of Gravitation is still quite adequate. As long as you're not near a supermassive object like a black hole, the effects predicted by general relativity are more subtle.

In 1916, Einstein's theory of general relativity offered a radical new view of gravity. Matter was no longer an independent object floating in space putting out feelers of force to attract another object. Instead, the presence of matter actually bent four-dimensional space-time. The more massive the object, the greater the curvature. Such bending has often been pictured in three dimensions as the effect a ball would have in indenting a flexible rubber mat. You could now think of a planet, comet or light ray as following the shortest path in that warped space-time. It's a geometrical interpretation that can be tested.

In his own writings on relativity, Einstein listed what came to be known as the "three crucial experiments," effects not predicted by Newton:

- The advance of Mercury's perihelion (closest point to the sun) by about 43 arc seconds per century after subtracting out the effects of precession and the other planets.
- The gravitational bending of starlight at the limb of the sun.
- The gravitational redshift.

The first was an effect long known but unexplained until relativity. It was due to

ITS DAY IN THE SUN

the warping of space near the sun. The second was observed during a solar eclipse in 1919, making Einstein world famous. The third points out the problems experimental relativity has had to face.

That last "crucial" experiment is based on relativity's prediction that gravity will cause time to slow down. The stronger a gravitational field, the slower a clock will run. This also means that atoms on a heavy mass such as the earth will emit light at lower frequencies (fewer cycles per second) than atoms out in space. A lower frequency, in turn, means the light's wavelength will be longer, shifted toward the red end of the spectrum (hence the term "gravitational redshift").

The effect is minuscule in the neighborhood of the earth and moon. A clock on the earth's surface will lose only billionths of a second each day compared to a clock in outer space. When general relativity was first proposed, scientists did not have the instruments or techniques to measure such a small difference. They had to wait until 1959 when R. V. Pound and G. A. Rebka of Harvard University used the Mössbauer effect to make the first accurate check. Mössbauer saw that under suitable conditions radioactive nuclei can emit gamma rays at very precise frequencies. The precision is so great that Pound and Rebka were able to detect a change in the frequency of a gamma ray as it traveled from the basement to the top floor of a physics laboratory. The gravitational redshift over those 74 feet was just as Einstein predicted.

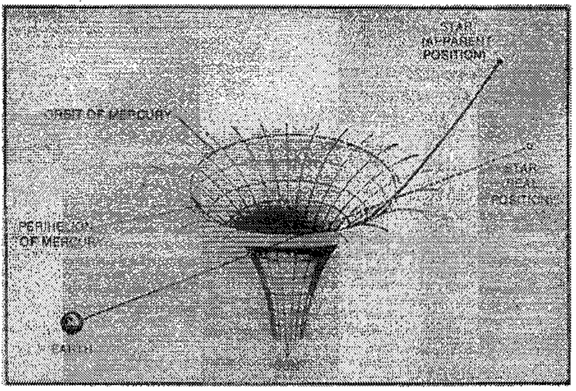
Since then, scientists have continued to both refine the techniques for those three crucial experiments and to devise new tests to demonstrate the validity of this geometric perception of space-time. The light deflection effect, for example, was reconfirmed when signals from the Viking spacecraft at Mars were found to be delayed when passing near the sun. Around the same time, Robert F. C. Vessot of the Harvard-Smithsonian Center for Astrophysics and Martin W. Levine, now with Frequency and Time Systems in Massachusetts, carried out a gravitational redshift experiment in collaboration with NASA that proved to be the most accurate test to date. It was also a first — the first to send an atomic clock into space for a relativity test. Stanford University physicist C. W. F. Everitt has described the project as "one of the most beautiful gravitational experiments done" up to this time.

On June 18, 1976, the special 90-pound hydrogen maser clock was rocketed 10,000 kilometers above the earth's surface from Wallops Island, Va. The basic idea of the experiment was simple — monitor the oscillations of the atomic clock as it traveled almost vertically up and down in the earth's gravity field. The frequency of the space clock as compared with an earthbound clock should change as the gravitational potential changes. Carrying out this idea, however, was another matter.

"It was an extraordinary experiment in that the instruments had no settling time in just two hours of flight," says Vessot. "It all had to work right away from start to finish. The clock also had to be able to withstand the shocks of the rocket stages."

A key problem during the test was discerning the subtle relativistic effects amidst the much larger changes that were occurring during the suborbital flight. As the space-bound clock was monitored by a ground station in Florida over a microwave link, its frequency was changing not only because of the variation in gravitational potential but also because of ordinary doppler effects arising from the motion of the probe (just as the sound of a siren will go up or down in pitch when it is going either toward or away from you). In fact, the doppler effect was 100,000 times larger than the gravity effect.

Vessot and Levine solved this problem by operating a doppler-canceling system while the clock was in space. This system continually relayed a signal from the ground-based clock to the space probe and back. The two-way transmission caused that signal to be doppler-shifted twice, once on the way up and again on the way down. This information was then used to subtract out the one-way doppler shift in the space clock's signal, thus leaving only the relativistic effects.



Einstein's theory of general relativity presented a new view of gravity. The presence of matter, like the sun, essentially warps the space around it. Starlight gets deflected from a "straight" path and Mercury's perihelion advances by following the curved space.

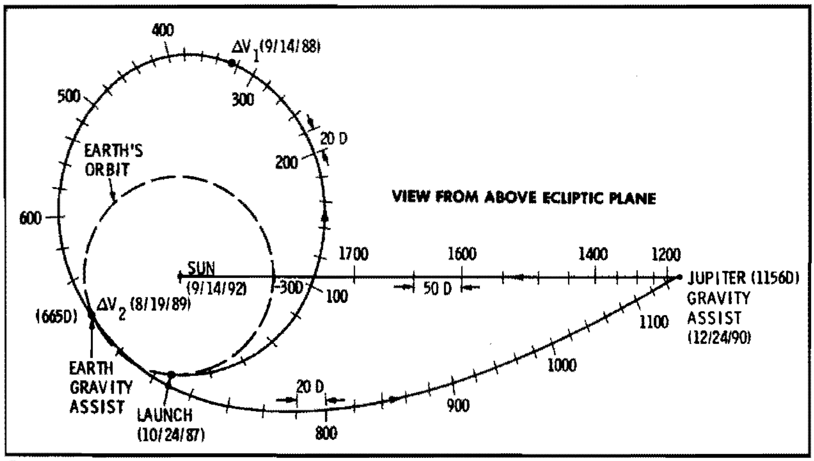
Contemporary Astronomy

Although preliminary results of this space test have been published, the final determination was only recently announced. At 10,000 km above the earth where gravity has loosened its grip, a clock would gain one second every 73 years. Vessot told SCIENCE NEWS that the gravitational redshift predicted by Einstein's general relativity was upheld within an accuracy of .014 percent, almost 100 times better than previous measurements.

By proving that atomic clocks can be made spaceworthy, the Vessot-Levine experiment helped pave the way for more extensive relativity tests in outer space, such as those included on the proposed solar probe mission. On that mission the effects of the sun's gravity will be studied by a method that has been around since Newton saw that famous apple drop to the ground. A freely falling body will be closely observed as it moves in the sun's gravitational field. There is, however, one problem. The solar probe, our modern-day apple, will not be entirely free falling. It will be buffeted by a large light pressure and particle flux emanating from the sun. So a thruster system has been incorporated into the probe's design to cancel those nongravitational forces and make the probe "drag-free." By then following the probe's movements in its trajectory around the sun with a highly accurate doppler tracking system, the sun's gravitational field can be mapped out in a sense. The angular momentum, for example, could be measured by seeing how the sun drags space around with it as it rotates (the relativistic "frame-dragging" effect). "Here we have a situation where the tracking data contain a fascinating combination of signatures, some resulting from the shape of the space-time metric owing to the sun's gravity, and some resulting from the sun's mass distribution and the angular momentum of the sun," says Vessot. It will be up to the gravity and relativity specialists to unravel those effects.

The solar probe will do most of its work in a very short time, a few days before and after its closest approach to the sun. But it will take five years to get there. "The inherited earth velocity of 30 kilometers per second must be reduced to nearly zero to fly into the sun," says James E. Randolph, solar probe study leader at the Jet Propulsion Laboratory. "Planetary gravity assist is needed to supply the largest percentage of this energy."

If the solar project proceeds as planned, the 1,300-kilogram spacecraft will be launched by the space shuttle in late 1987 and spend two years looping around earth's orbit until it once again swings by its home planet. The added boost will send it off on a one-and-a-half-year cruise to Jupiter where it will swing around and head back toward the sun. But the probe will not be idle during its long journey in space. On the way to Jupiter, NASA hopes to hunt down another relativistic quarry that until now has not been firmly pinned down — gravity waves.



Proposed Earth-Jupiter gravity assist trajectory for the solar probe.

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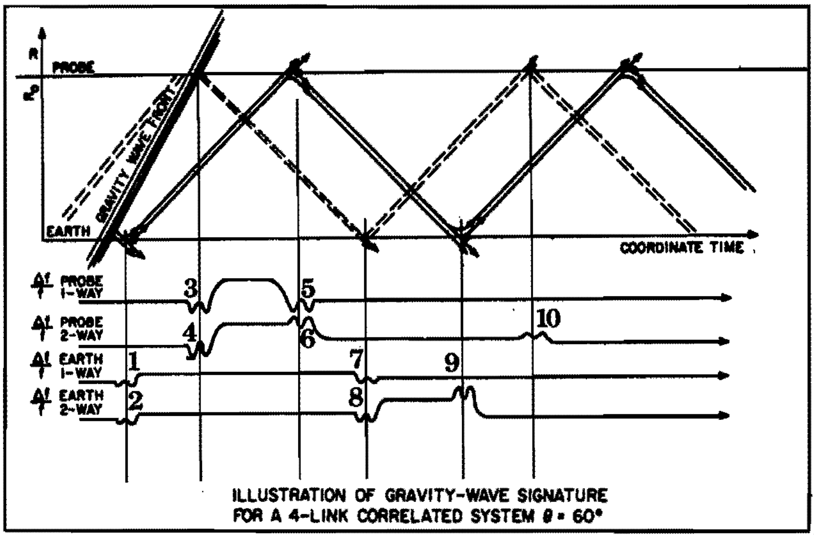
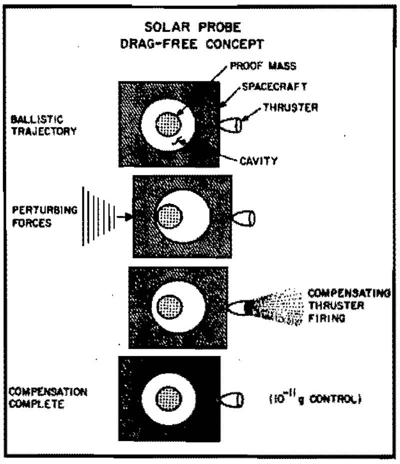


The characteristic ten pulses that would be produced by tracking a gravity wave that is traveling between earth and a probe out in deep-space.

Vessot and Levine

When a charged particle changes its speed or moves in a circle, it radiates an electromagnetic wave. In a similar fashion, general relativity predicts that when a massive object accelerates or vibrates in a certain way it will radiate a gravitational wave. Theory says, for instance, that gravity waves are produced as the earth orbits the sun. But the gravitational energy from such an event is much too small to measure. The gravitational fields of the earth and sun are too weak. Detectable low-frequency waves would come from more spectacular events, like the collapse of astrophysical objects millions of times heavier than the sun. As those gravitational pulses arrive at our solar system possibly once or twice a week, cosmologists believe they may be observable with the extremely accurate doppler tracking of a spacecraft located 100 million miles or more from the earth.

Vessot envisions a tracking system similar to the one used in his gravitational redshift experiment and has proposed that it be used on the solar mission. As the gravity wave burst passes by the earth, it would cause the frequency of an earth-bound clock to change by an infinitesimal amount. Traveling through the solar system at the speed of light, the wave would later affect a clock on the solar probe in the same way. A unique gravity wave "signature" would be built up by communicating those frequency changes over four microwave links between earth and the probe. "The signature would consist of ten pulses whose amplitudes and times of arrival would be related to the angle between the earth-probe line of sight and the direction of the gravity wave's propagation," says Vessot. "It's a valuable method because the chances of the signature coming from anything other than a gravity wave are extremely small."



To cancel out nongravitational forces like light pressure from the sun, a special thruster system will make the solar probe "drag-free".

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Such a discovery would open up a whole new frontier of astronomy. Our eyes on the universe would no longer be restricted to seeing just electromagnetic waves such as X-rays, radio waves and visible light. We would be perceiving a completely new form of radiation, a type that would not be absorbed by intervening dust clouds and so lost to our view. Just as radio astronomy introduced us to celestial objects never even imagined in science fiction, a gravity wave "telescope" might do the same. Perhaps pulsars and quasars will seem commonplace in comparison with the exotic astrophysical events that gravity wave astronomy might reveal.

"When we do this — it's not a question of if — it will be the most important form of astronomy we're going to face," says Vessot. "As exciting as when Galileo first turned an optical telescope on the skies. With gravity waves we'll be looking at the reverberations of the origin of galaxies. They'll be the oldest thing we can look at besides the cosmic background radiation. It will enable us to go back to the dawn of creation."

The solar probe is only one of many projects being planned to conduct relativity experiments both here on earth and out in space. Some will be extensions of the three crucial experiments; others will look at additional aspects such as the frame-dragging effect or whether gravity is growing weaker in time. It all means that experimental relativity is finally catching up to its theory. In the words of gravitation experts Charles Misner, Kip Thorne and John Wheeler in their book *Gravitation*, "General relativity is no longer a theorist's Paradise and an experimentalist's Hell." ☐