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THE DIRECTOR'S REPORT:

Investigation, Research, and Discovery

> "IT IS PROPOSED TO FOUND IN THE CITY OF WASHINGTON, AN INSTITUTION WHICH…SHALL IN THE BROADEST AND MOST LIBERAL MANNER ENCOURAGE INVESTIGATION, RESEARCH, AND DISCOVERY…"
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> *—Andrew Carnegie (1902)*[1]

When Andrew Carnegie gave his initial gift establishing the Carnegie Institution of Washington, his vision for promoting science was "to discover the exceptional" individual and to provide an opportunity for that scientist to devote his or her attention to the pursuit of work for which he or she "seems specially designed." The archetype of that vision, by tradition, is the bench scientist who alone or perhaps with a few close collaborators conceives and carries out the experiments needed to advance a particular line of scientific inquiry. Among the leaders of the institution throughout its history, however, have been supremely gifted administrators of large scientific endeavors—epitomized by Vannevar Bush, who while president of the Carnegie Institution ably led the nation's Office of Scientific Research and Development during World War II. As the global scientific enterprise has grown in size and complexity, the question of the scale of scientific programs appropriate to the institution has been a natural topic for continued discussion. Most such deliberations have reinforced the traditional view of Carnegie's vision—that the role of the institution is to invest in the creative individual. Merle Tuve, director of the Department of Terrestrial Magnetism (DTM) from 1946 to 1966, was an outspoken advocate of such a position. He wrote that "no array of feedback arguments will convince very many of us that the real germ of new knowledge is the product of team activity or the result of large-scale instruments or implements… I believe we should take the firm position on the point that the support of true basic research is the support of ideas and that this always means the support of a creative investigator."[2]

There are nonetheless topics of great scientific interest that require access to facilities or instrumentation beyond the means of a single laboratory or department. One cannot study most processes in or beneath the Earth's oceans without oceanographic ships, one cannot carry out most frontier projects in observational astronomy without modern telescopes, and one cannot investigate the details of the planets of our solar system without spacecraft. For the past five and a half years I have served as the Principal Investigator for a spacecraft mission to study the planet Mercury. That spacecraft—MErcury Surface, Space ENvironment, GEochemistry, and Ranging, or MESSENGER—was launched in August 2004 and after a long and circuitous route through the inner solar system will become, in March 2011, the first probe to orbit Mercury. Is the leadership of a spacecraft mission of exploration—an effort that surely qualifies as a large-scale "product of team activity"—consistent with the expressed intent of Andrew Carnegie and

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[1] Andrew Carnegie, Deed of Trust, 1902, Year Book no. 1, p. xiii (Washington, D.C.: Carnegie Institution of Washington, 1903).

[2] Merle A. Tuve, "Is science too big for the scientist?" *Saturday Review* 62, no. 23, pp. 49-52, June 6, 1959.

Left: The MESSENGER spacecraft left Earth at 2:15:56 a.m. EDT on August 3, 2004, aboard a Boeing Delta II rocket launched from Cape Canaveral Air Force Station, Florida. (Image courtesy The Johns Hopkins University Applied Physics Laboratory and NASA.)

the resolute opinion of Merle Tuve that the focus of our institution should be on the creative investigator? I believe that it is.

The innermost planet has been visited by only a single spacecraft. *Mariner 10* flew by Mercury three times in 1974 and 1975. Each flyby was separated by two Mercury "years"—two revolutions of Mercury about the Sun. Mercury is in a rotational state unique in the solar system, in that the planet's spin period is exactly two-thirds of the rotational period. As a consequence the solar day on Mercury—the time between successive passages of the Sun overhead—is equal to two Mercury years. *Mariner 10* therefore saw the same side of Mercury lit by the Sun during each of its three close encounters, and more than half of Mercury was never imaged. The images of the surface that *Mariner 10* did obtain stimulated arguments about the planet's geological history that continue to the present, and other discoveries by *Mariner 10* raised many questions still not answered.

Even before the *Mariner 10* mission, it was known that Mercury is unusually dense. After correcting for the effects of self-compression by interior pressure, the "uncompressed" density of the material inside Mercury is substantially higher than that of any of the other planets. Because Mercury, like the other inner planets, is composed of rock and metal, the high density implies that the mass fraction of metal occupying a central core in Mercury is at least 60%, a fraction twice as high as that for the Earth (Fig. 1). Mercury's high metal fraction must date from early in solar system history when the inner planets were assembled from material within the nebula of dust and gas that surrounded the young Sun. One hypothesis is that the material of the innermost nebula, from which Mercury was later predominantly accreted, was enriched in metal because the lighter silicate grains were preferentially slowed by interaction with the nebular gas and tended to fall into the Sun. Another hypothesis is that after Mercury accreted to full planetary size and a central metal core differentiated from a silicate shell, the silicate fraction was partially vaporized by a high-temperature nebula and the vapor was driven off by a strong solar wind. A third hypothesis—championed by DTM's George Wetherill—is that after Mercury accreted

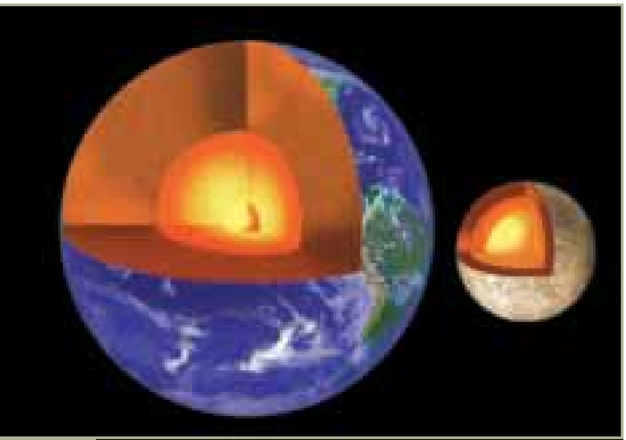

Fig. 1. On the basis of its bulk density, Mercury must have a central core consisting mostly of iron metal and occupying a fraction of the planetary interior much larger than that for Earth's core (left). Earth has a solid inner core and a fluid outer core, shown to approximate scale; Earth's magnetic field is sustained by a hydromagnetic dynamo in the outer core. The nature of Mercury's core and the origin of the planet's magnetic field remain to be determined. (Image courtesy NASA and The Johns Hopkins Applied Physics Laboratory.)

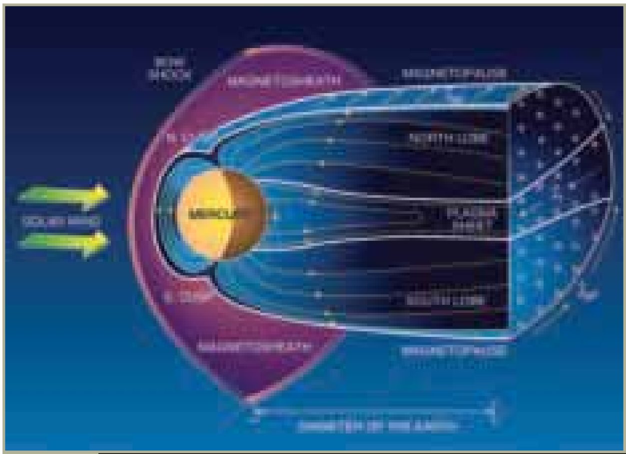

Fig. 2. Observations by *Mariner 10* and extrapolations from spacecraft measurements near the Earth suggest that the magnetosphere of Mercury is a miniature version of the Earth's magnetosphere generated by the interaction of the Earth's internal magnetic field with the solar wind. Many details of Mercury's magnetic field and magnetosphere are not understood, however, in large part because of the limited sampling by *Mariner 10*. (Figure courtesy James A. Slavin, NASA Goddard Space Flight Center.)

and differentiated core from mantle, the planet was the target of a giant impact that stripped off and ejected much of the outer silicate fraction. These three hypotheses, which differ strongly in their implications for how the inner planets came to differ in bulk composition, are testable because they predict different outcomes for the major-element chemistry of the silicate fraction of the planet. *Mariner 10* carried no chemical remote sensing instruments, and ground-based efforts to deduce compositional information about Mercury's surface from the identification of mineral absorption bands in reflected visible and infrared radiation have had only limited success. Sorting out how Mercury ended up a dominantly iron planet requires chemical remote sensing from an orbiting spacecraft.

One of the major discoveries of *Mariner 10* was that Mercury has an internal magnetic field. This was a surprising finding, because a planet as small as Mercury should have cooled over its lifetime to a greater extent than Earth. Earth's magnetic field is known to arise through the dynamo action of convective motions in its fluid metal core, and numerical models of interior cooling predict that a pure iron core in Mercury would have fully solidified by now. The field detected by *Mariner 10* appears to be predominantly dipolar, like Earth's field, but the dipole moment is smaller by a factor of about 10^3. An Earth-like hydromagnetic dynamo in a fluid outer core is only one of several ideas postulated to account for Mercury's magnetism. A fossil field in Mercury's crust remaining from an earlier era when a core dynamo was active is another possibility, and more exotic dynamos (e.g., thermoelectric currents driven by temperature variations at the top of a metal core with a bumpy outer boundary) have also been suggested. These hypotheses can be distinguished because they predict different geometries for the present planetary field, and magnetic field measurements made from an orbiting spacecraft can separate internal and external fields and map the internal field. Mercury's magnetosphere—the envelope of space dominated by the planetary field and defined by the interaction of that field with the solar wind plasma streaming from the Sun—is the most similar to Earth's magnetosphere among the planets, but with important differences (Fig. 2). The solar wind fields are stronger closer to the Sun; Mercury occupies a much larger fractional volume of its magnetosphere because of its weaker internal field; and Mercury lacks an ionosphere, the site of important current systems in Earth's magnetosphere. Mercury's magnetosphere is therefore an important laboratory for generalizing our understanding of Earth's space environment.

Fig. 3. *Mariner 10* images of Mercury were obtained with three color filters. This mosaic, with false colors selected to emphasize spectral variations with chemistry and mineralogy seen on the Moon, illustrates that geological units on Mercury can be distinguished on the basis of color and that information on mineralogy is derivable from surface spectral reflectance measurements. (Image courtesy Mark Robinson, Northwestern University.)

The geological history of Mercury has been deduced from the images taken by *Mariner 10*, but there are many unanswered questions. Mercury's surface consists primarily of heavily cratered and smooth terrains (Fig. 3) that are at least superficially similar in morphology and relative stratigraphic relationship to the highlands and geologically younger maria, respectively, on the Moon. Whereas the lunar maria are known to consist of basaltic lava flows on the basis of samples returned by the Apollo missions and orbital images of frozen lava flow fronts in several maria, the smooth plains on Mercury are higher in albedo (i.e., brighter in reflected light) than the lunar maria and no volcanic features can be seen in the relatively coarse-resolution *Mariner 10* images. The role of volcanism in Mercury's history is therefore an open issue. From the standpoint of large-scale deformation, Mercury shows evidence for an

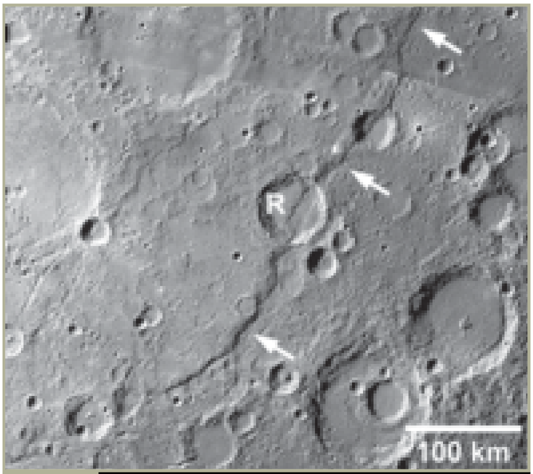

Fig. 4. The longest known lobate scarp on Mercury is Discovery Rupes, shown in this *Mariner 10* image mosaic. The scarp is 550 km long and displays 1 km or more of topographic relief. Arrows denote the approximate direction of underthrusting of the crustal block to the right beneath the block to the left. The crater Rameau (R), transected by the scarp, is 60 km in diameter. (Image courtesy Mark Robinson, Northwestern University.)

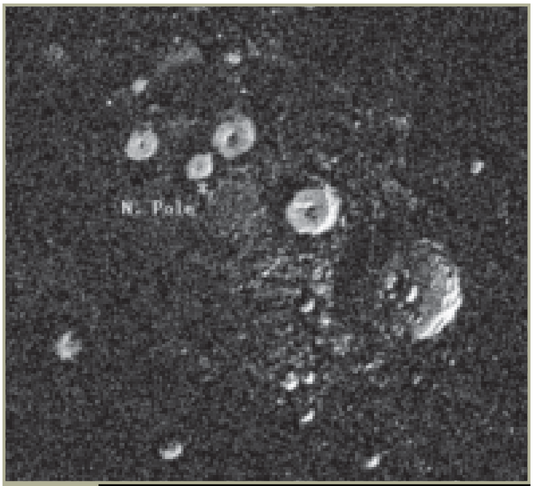

Fig. 5. This radar image of the north polar region of Mercury, obtained at the Arecibo Observatory in 1999, demonstrates that Mercury's radar-bright polar deposits lie within the floors of large impact craters. The radar direction is from the upper left, the resolution is 1.5 km, and the image is shown in polar projection. (Image courtesy John Harmon, Cornell University.)

interesting history. The most prominent deformational features are the lobate scarps (Fig. 4), thought to be the surface expression of large thrust faults produced by horizontal shortening of the crust. The apparently random orientations of these scarps on all terrain types has led to the interpretation that they are the product of global contraction—a shrinkage of the planet as the interior cooled and the core solidified. Global shrinkage was at one time suggested as an explanation for the formation of mountain systems on Earth, but that idea was discarded with the acceptance of plate convergence at subduction zones. Mercury may be the one planet where a record of such shrinkage is preserved. A critical test of that conclusion will be possible when images are taken of the hemisphere that *Mariner 10* did not view.

Mariner 10 detected the presence of hydrogen, helium, and oxygen in Mercury's tenuous atmosphere. Ground-based spectroscopic observations led to the discovery of additional species, including sodium, potassium, and calcium. Most of these constituents are too abundant to be derived from the solar wind, and their atmospheric lifetimes are much shorter than the age of the planet, so there must be steady sources at the planetary surface. The specific processes controlling the sources and sinks of atmospheric components are not well known, however. Key information from an orbiting spacecraft that would help to discriminate among competing hypotheses are the detection of additional species and the monitoring of atmospheric properties as functions of time of day, solar distance, and level of solar activity. One or more additional volatile species appear to be present at the surface near the planetary poles. Ground-based radar imaging of Mercury led to the discovery in 1991 of radar-bright polar deposits localized within the floors of near-polar impact craters (Fig. 5). The deposits have radar reflectivities and polarization characteristics that are well matched by water ice, although other materials have also been suggested. Ices are stable for billions of years in such areas because Mercury's obliquity (the tilt of its spin axis from the normal to the orbital plane) is nearly zero and the floors of near-polar craters are in permanent shadow and consequently very cold.

Remote sensing measurements from an orbiting spacecraft are needed to confirm the composition of these trapped volatiles.

Given the broad sweep of issues addressable with a Mercury orbiter, why did 30 years pass between the first Mercury flyby of *Mariner 10* and the launch of the next mission to the innermost planet? The answer to this question has several parts. After *Mariner 10*'s discoveries, there was widespread interest in a Mercury orbiter mission, but it was thought that conventional propulsion systems could not be used to inject a spacecraft into Mercury orbit because the required change in velocity was too large. In the mid-1980s multiple gravity-assist trajectories were discovered that could achieve Mercury orbit insertion with existing propulsion systems, but the 1980s were a difficult era in the history of planetary mission launches. NASA had adopted the policy that the Space Shuttle would be the sole launch vehicle for its missions. At the same time, the planetary exploration program was emphasizing large, complex, and costly spacecraft, which for budgetary reasons tended to be launched infrequently. The *Challenger* disaster in 1986 shut down NASA's launch capability and created a queue of planetary missions awaiting flight. By 1989, when flagship missions to Jupiter and Venus were launched, 11 years had passed since the previous U.S. planetary mission had left Earth. In the early 1990s, NASA reexamined its approach to planetary exploration, and Wesley Huntress—now the director of the Geophysical Laboratory but at that time the NASA Associate Administrator for Space Science—initiated the Discovery Program.

The Discovery Program is a partnership between NASA and the planetary science community whereby mission opportunities are regularly competed. Limits are set on total mission cost, development time, and launch vehicle, but a proposing team is free to offer any mission concept that satisfies those limits. Review panels then recommend for selection the mission proposals that offer compelling scientific return but are at the same time technically and financially feasible. Mercury was the target of a number of early unsuccessful proposals to the Discovery Program, but the MESSENGER mission concept was born when engineers and space scientists at The Johns Hopkins University Applied Physics Laboratory (APL) came up with mission and spacecraft designs that looked practicable. In 1996 APL approached me about serving as Principal Investigator for a Discovery Program proposal, and after a couple of early discussions I agreed. We assembled a team of scientific investigators, and we selected a set of payload instruments that could make all of the global measurements discussed above. Our proposal was selected for further study, but our second-round effort in 1997 was deemed too risky by NASA, in large part because of concern with the ability of the spacecraft to survive the harsh thermal environment at Mercury. APL carried out an

Fig. 6. The complex process of assembling and testing the MESSENGER spacecraft and mating it to its launch vehicle extended over a year and a half. Shown is the spacecraft on July 14, 2004, after it was attached to the payload assist module of the Delta II third stage at Astrotech Space Operations in Titusville, Florida. The two flat, reflective panels are the solar arrays stowed in their launch positions. (Image courtesy NASA and The Johns Hopkins University Applied Physics Laboratory.)

Fig. 7. Members of the Department of Terrestrial Magnetism staff are shown on November 3, 2004. First row (from left): Timothy Mock, Lucy and Charles Flesch, Linda Warren, Brian Savage, Katherine Kelley, Pablo Esparza, Aki Roberge, Mercedes López-Morales, Adelio Contrera, and Roy Dingus. Second row: Susan Webb, Erik Hauri, Sandra Keiser, Alan Linde, and Richard Carlson. Third row: Alan Boss, Nelson McWhorter, Steven Shirey, Kevin Wang, Hannah Jang-Condell, Maceo Bacote, Lindsey Bruesch, Alexis Clements, Jennifer Snyder, Oksana Skass, Maud Boyet, Terry Stahl, and Pedro Roa. Fourth row: Gotthard Sághi-Szabó, John Graham, Fouad Tera, Scott Sheppard, Janice Dunlap, John Chambers, Sean Solomon, Maria Schönbächler, Sara Seager, and Brenda Eades. Fifth row: Jianhua Wang, Kevin Burke, Jay Bartlett, Taka´aki Taira, Paul Silver, Henner Busemann, Selwyn Sacks, Daniela Power, Gary Bors, Charles Hargrove, Georg Bartels, Brian Schleigh, and Bill Key.

extensive testing of critical spacecraft components under high-temperature vacuum conditions, and we reproposed in 1998. We were again selected for a second phase of study, and after a thorough second review MESSENGER was selected for flight in July 1999. Within a week of selection, Congress had cut MESSENGER and several other missions from the NASA budget then under consideration, but by the passage of the final appropriations bill that year MESSENGER had been restored.

Between mission selection and launch were five event-filled years. We saw multiple changes in programmatic management at NASA and heightened concern for mission risk as a number of other robotic and piloted missions suffered losses. The MESSENGER team struggled with changes in project management and engineering subsystem leadership, late delivery of key subsystems and instruments, multiple failures of critical electronic components, consequent schedule delays, and two postponements of launch opportunities. A robust and thoroughly tested spacecraft nonetheless was delivered, mated to its launch vehicle (Fig. 6), and successfully sent on its multiyear journey toward Mercury.

The MESSENGER mission carries two notes of irony. The first is that one of the principal objectives of the mission—to understand Mercury's magnetic field and its relationship to the Earth's magnetic field—runs counter to the fact that terrestrial magnetism has not been a major focus of research at DTM for nearly half a century.

The second irony is that the organization that designed and built the MESSENGER spacecraft and is now managing the mission is APL, established by Merle Tuve during World War II as an off-campus laboratory to complete the development of the antiaircraft proximity fuze. Notwithstanding Tuve's admonition that a large-scale "product of team activity" is rarely if ever a "germ of new knowledge," the members of the MESSENGER team at the institution that Tuve began are working hard to ensure that the spacecraft successfully carries out its full mission. Given its broad objectives, MESSENGER surely fits Andrew Carnegie's intention that this institution "encourage investigation, research, and discovery."

—Sean C. Solomon