HIGH-POWERED FUNDAMENTAL PHYSICS FROM MERCURY

Proposed Experiments

Due to priorities and constraints on spacecraft and mission design, instruments and flight trajectories for NASA planetary missions have not been optimized for fundamental physics studies. Small improvements in measurements of relativistic or gravitational parameters, and hence limited confirmation of fundamental theories based on observational evidence, have come about as a secondary benefit from spacecraft tracking or from groundbased measurements.

Such experiments were not considered by the Space Physics Mercury Orbiter Working Group (see Issue 4 of this newsletter). However, one of the proposals submitted (but not selected for further study) as part of the Discovery Initiative was a Mercury Geophysics Mission, which emphasized measurement of gravitational parameters with accuracies on a scale of centimeters (see Issue 5 of this newsletter). This mission would have provided an estimate of the Love Number, k_2. Such a measurement would constrain thermal models and the size of the fluid core.

As this issue will show, data from a Mercury mission with a transponder flown in a polar, high-altitude, elliptical orbit, either on a subsatellite or the spacecraft itself, could provide measurements of parameters of fundamental importance in the understanding of gravity and general relativity. According to scientists in this field [1–3], measurements derived from a series of orbital time-delay observations combined with currently available groundbased measurements of Mercury would provide the basis for (1) testing theories of gravitation and general relativity; (2) direct measurement of J_2, the Sun's gravitational quadrupole moment; (3) looking for (placing an upper limit on) the time variation of the gravitational constant G (sometimes expressed as $\dot{G}/G$); and (4) updating mercurian ephemerides and figure determinations for future American or joint international flight projects, as well as constraining internal structural models and history.

Testing of Fundamental Theories of Gravitation

Precise determination of the motion of Mercury provides a way to test the gravitational interaction to post-Newtonian accuracy and to search for possible long-term variations in the gravitational field interactions of the Sun. The Sun-Mercury system provides an excellent natural system for testing general relativity for two reasons: (1) Mercury is the closest to the Sun of any of the planets, and (2) its eccentricity is large (e = 0.2056). Hence, the relativistic precession of
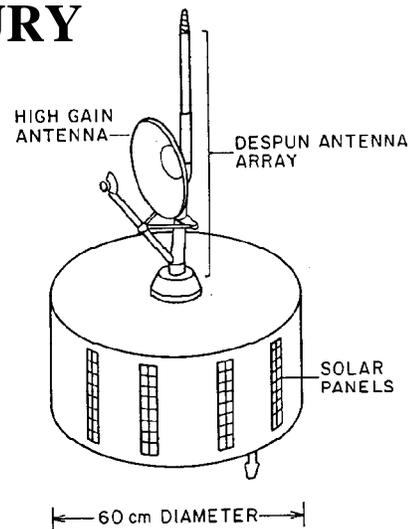

Fig. 1.

its perihelion is relatively large and easy to measure, at 42.98 arcsec per century, compared to other planets.

Historically, observations of Mercury have been crucial in testing general relativity. In 1882, Simon Newcomb derived the modern value of the excess precession of 43 arcsec per century. Twenty years later, he thought he had found the explanation for this departure from Newtonian gravity, in the form of a zodiacal dust cloud proposed by Seeliger, and assumed Newtonian gravitation was essentially correct. Now, scientists generally disagree: In fact, this excess is assumed to be a confirmation of the theory of general relativity, and is derived naturally from the theory with no free parameters needing adjustment.

Observational evidence obtained during this century has been used to support not only general relativity, but two alternative theories of current interest in gravitational field formation: (1) Superstring theory gives rise to general relativity and scalar field theories at the lower energy limit (as in our solar system). Whereas general relativity is a four-dimensional vector theory (space plus time), scalar field theory, originally motivated by Brans-Dicke, is based on a tensor that doesn't have indices, and is essentially locally defined. These theories give rise to increased precession. (2) Nonsymmetrical gravitation theories [4] are based on nonsymmetrical tensor distribution, and predict decreased precession.

Thus, each theory modifies the post-Newtonian field of the Sun with the consequence of changing the value of relativistic precession

from its general relativity value. Observations of Mercury motions can measure J_2, the solar gravitational quadrupole moment. Such observations also provide validation of the J_2 inferred from helioseismology data.

Potential Gains from Orbital Observations

Range and Doppler data acquired from a dedicated Mercury Orbiter or subsatellite could be used to determine the orbit of Mercury and derive its precession more precisely. The orbital measurements technique would consist of determining the motion of the center of mass of Mercury by spacecraft tracking. An ideal mission configuration would be a high-altitude (2440 km), circular, nearly polar orbit for a small transponder satellite, possibly carried as a subsatellite and launched from a larger spacecraft. Circular, lower-altitude or more highly elliptical orbits with lower inclinations could still be useful. One version of the proposed satellite [5] is shown in Fig. 1. This 50-kg, cylindrical, spin-stabilized spacecraft is essentially a scaled-down version of the one flown for the Pioneer Venus mission.

Determination of the orbit of the spacecraft with respect to the center of mass of Mercury is crucial. Preliminary calculations indicate that measurements of distance from the center of mass of the Earth to the center of mass of Mercury should now be achievable with 10-m or better accuracy [6,7], a conservative figure that is based on previous mission tracking capability. The 10-m accuracy is consistent with radio science experience on Mariner 9 and Viking Orbiters at Mars with 1970s technology. Many scientists agree that a Mercury mission, configured as described above, could be designed to yield accuracies much improved over the conservative figure mentioned above with less tracking time. Such improved accuracies, involving only a small increment of additional effort when a mission is being considered, would result in a large increment in our understanding of fundamental and mercurian gravitational physics.

In fact, Bender and Ashby [8] predict that submeter accuracies, down to 6 cm in fact, are well within reach, providing that some new conditions are met. This much higher accuracy would require, for example, the addition of K-band capability for the Deep Space Network. It is based on 1×10^{-14} Doppler accuracy and 3-cm range accuracy, which was supposed to have been implemented for the Galileo mission. (These measurements would also provide the basis for a map of Mercury's gravitational field, the least known of the terrestrial planets, for up to degree and order 10.) A new, small transponder with X- and K-band ranging systems using a 50-MHz offset sidetone at K band would be required. Thus, improvements in accuracy, with which parameters of interest could be determined, would then be 2 orders of magnitude better than accuracies achievable on previous missions.

Preliminary analyses [1,9] have demonstrated that flying a Mercury Orbiter will give considerably more accurate measurements than groundbased observations alone over the same period of time, given even present tracking capabilities. The requirements for the mission proposed by Vincent and Bender [9] are (1) 10-min observation times would be used; (2) observations would be taken during a minimum of 40 independent 8-hr arcs taken over a 2-yr period, carefully chosen to minimize error, by, for example, taking measurements only in full sunlight; (3) arcs are carefully chosen temporally and spatially, to minimize sources of error and optimize observing conditions; and (4) data would be collected over a minimum of 2 yr.

Some error analysis parameters for which uncertainties are considered [2] are (1) the six orbital elements of the Earth (the Keplerian elements: semimajor axis, eccentricity, three rotational directions, perihelion); (2) the same six orbital elements for Mercury, which are assumed to be known initially to the same accuracy; (3) the relativity parameters, which indicate how much space is curved by mass, known as gamma and beta; and (4) the solar quadrupole coefficient, J_2. Anderson and co-workers indicate that gamma in particular could be determined with far greater precision than previously, allowing further improvement and refinement in the development of gravitational theories. More analysis of the proposed experiments is needed before their full po-tential is realized.

Theoretical physicists agree that such orbital experiments are useful and complementary to groundbased observations in the testing of fundamental theories. Improvement of at least 2–3 orders of magnitude for some orbital and figure parameters, particularly the center of mass and pole position, is feasible with the proposed theoretical physics experiments, from the orbiter experiment, groundbased experiments described below, or with a combination of both, which will improve the accuracy of future groundbased experiments.

Ongoing Groundbased Radar Observations

An ongoing joint venture involving the Goldstone Solar System Radar Group at NASA/JPL, the Arecibo Observatory in Puerto Rico, and the Harvard-Smithsonian Center for Astrophysics is designed to test gravitational theories through acquisition and analysis of Mercury radar data. In addition, the Mercury radar observations allow a direct measurement of the Sun's gravitational quadrupole moment from the secular and short-period effects on Mercury's orbit. All other methods are model-dependent even if they were unambiguous.

The project [10], which has been in operation for four years, is designed to take 50–100 observations over a 5–10-yr period. So far, most of the observation runs have been successful. These observations can improve our knowledge of gravitational physics because the experiment is designed to produce "closure points." "Closure" is achieved by observing the same sub-Earth points (at given Mercury longitudes and latitudes) at different epochs. Figure 2 shows closure points if the motion were confined to a two-dimensional plane. Fortunately, in three dimensions, a radar observation does not simply determine a range at a single point on the surface of Mercury. Instead,
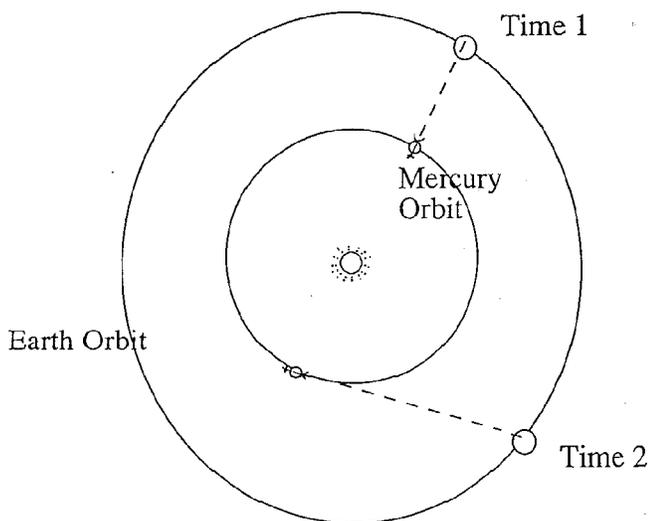

Fig. 2.

a profile of the relative heights is obtained that extends along the path of the subradar point (the Doppler equator) for 10° of longitude or so.

The only requirement for "closure" is that profiles obtained on two different days have part of a footprint in common. The common topography drops out when the ranges are differenced, thus removing this very large "noise" source (from the point of view of testing theories of gravity, not of surface geoscientists!). These data have the full precision of radar time-delay observations, which are 0.5–1.0 μs for current Goldstone observations. For nonclosure ranges, this precision must be degraded to 10–20 μs to account for topography remaining after the surface has been fit with low degree and order spherical harmonical terms. Joint observations at Goldstone and Arecibo must be carried out, where possible, in order to be certain of the relative calibrations of these two systems.

The primary objectives of the current analysis of Mercury ground-based radar data are (1) the determination of the excess relativistic precession of Mercury's perihelion, in excess of the inertial 530 arcsec/century from planetary perturbations, and (2) a determination of any possible time variation in the gravitational constant G as measured in atomic units. (Over the past half century, it has been suggested that G, defined as a constant in both Newton's theory of gravity and Einstein's theory of general relativity, may have a long-term variation coupled to the expansion of the universe.)

The new dataset presently being obtained, as described above, already appears to be of high quality. The new data available so far have already been combined with larger, older datasets by Anderson and co-workers to obtain preliminary solutions to parameters described above.

Solutions attempted for various parameters have demonstrated the sensitivity that can be expected from the continuation of these observations. The analysis of the extended dataset, with closure imposed, can be expected to result in improved inner solar system ephemerides, as well as more accurate determination of J_2 and improved assessment of gravitational theories.

Analysis of these observations is being provided by Shapiro of the Harvard-Smithsonian Center for Astrophysics and Anderson of JPL. A preliminary analysis of past and current data is given in a paper by Anderson et al. [11]. This paper combines major datasets acquired at all groundbased radar observatories during the planning and operation of the Mariner 10 mission with more current observations. Results are based on weighted least-squares fits to the following existing datasets along with available newer data: (1) 338 radar ranges for Mercury, 1966–1974, from Goldstone, Arecibo, and Haystack observatories; (2) 2 range fixes to Mercury from the Mariner 10 flybys, 1974–1975; (3) 157 radar ranges for Mercury from Arecibo, 1978–1982; (4) 60 radar ranges for Mercury from Goldstone, 1986–1988.

By using the cartographic longitude on Mercury as the independent variable, they found a significant trend in the radar ranging between 1966 and 1988, and attribute it to the noncircular, changing elliptical cross section for the equator of Mercury, as well as inaccurate orbit determination. After removal of this trend from the data, earlier radar ranging results are consistent with more recent ones and with Mariner 10 range fixes [1].

New Groundbased Results

The mean radius of Mercury had been determined independently of radar ranging. Fjeldbo et al. [12], using radio occultation data from the Mariner 10 flyby, obtained 2439 ± 1 km. Ash et al. [13] derived the same value from the first few years of radar ranging. Now, by combining all groundbased observations with the Mariner data, Anderson et al. [11] have determined the global shape of the equatorial cross section, and a more accurate value for the mean equatorial radius. The new longitude-dependent radius is given by 2439.88 + 0.45 cos(2L) + 0.42 sin(2L), where the longitude (L) is defined by the IAU convention. The estimate of realistic standard errors in the sine and cosine coefficients is 0.16 km, while the standard error in the mean radius is 0.3 km. The correlation between the three coefficients is insignificant. The maximum equatorial radius of Mercury is 2440.5 km at a longitude near 22 arcdeg, and the minimum is 2439.3 km at a longitude near 112 arcdeg.

Using radar ranging between 1966 and 1974, as well as Mariner data, Anderson and co-workers [14] found a value for Mercury's excess precession of 42.92 ± 0.20 arcsec per century. Using much the same data, except for Mariner 10 range fixes, Shapiro et al. [15] had obtained a value of 43.11 ± 0.21 arcsec per century. Recent analysis of radar ranging between 1966 and 1988, combined with Pioner Venus data, yields a slightly better agreement with the results of Shapiro et al., at 43.13 ± 0.14 arcsec per century. Further analysis of Mercury data alone will not decrease the estimate of error; the basic limitation on the accuracy is the strong correlation between orbital elements of Mercury and the Earth. In the near future, with the addition of the Viking Lander ranging to Mars between 1976 and 1982, the orbital elements of the Earth will be determined independently of the Mercury ranging, and consequently the standard error on the perihelion precession will be reduced to about 0.1 arcsec per century.

A similar limitation in using only Mercury data is evident in the current determination of a possible time variation in G as measured in atomic units. The value obtained for $\dot{G}/G$ [6] is $(4.5 \pm 3.5) \times 10^{-12}$ yr. With the introduction of the Viking Lander data for the Earth's orbital elements, the realistic standard error of $\dot{G}/G$ from the relative motions of Mercury and Earth alone should decrease to about 2×10^{-12} yr. The magnitude of this value indicates that the theoretical assumption that the gravitational constant is independent of time is still viable.

Helioseismologically based models predict a value of 1.7×10^{-7} with a 10% uncertainty for J_2. A determination of J_2 by Anderson and co-workers yields $(0.4 \pm 1.5) \times 10^{-7}$ where the error bars give some indication of the precision of the current determinations.

References

[1] Anderson et al. (1987) *Icarus, 71*. [2] Anderson et al. (1991) personal communication. [3] Vincent and Bender (1990) *JGR, 95.* [4] Moffet (1993) *Theory and Physics in Gravitational Physics.* [5] Bender et al. (1989). [6] Anderson et al. (1992). [7] Anderson and Kritcher (1993) personal communication. [8] Bender P. and Ashby N. (1989). [9] Vincent and Bender (1991). [10] Slade (1991) personal communication. [11] Anderson et al. (1991) *Proc. ASA, 9.* [12] Fjeldbo et al. (1976) *Icarus, 29.* [13] Ash et al. (1971) *Science, 174.* [14] Anderson et al. (1993) Sixth Marcel Grossmann Meeting on General Relativity. [15] Shapiro et al. (1976) *Phys. Rev. Lett., 36.*

Pamela Clark with inputs from J. Anderson, P. Bender, M. Slade, and T. Kritcher

THE BALL-BEARING BOWLING ALTERNATIVE: WILD STRIKES FOR POLAR ICE

This has been a fairly intense issue for all of you who are not theoretical physicists. We couldn't resist including something a bit lighter, in the form of a very imaginative proposal from Jonathan Post (*Space Science Institute Proceedings*, 1993), science and science fiction writer from Pasadena.

In our last issue we discussed proposals for Mercury missions and the startling discovery of radar-bright polar caps, interpreted to be ice caps, on our favorite planet. In response, Mr. Post and others proposed flying a Discovery-class polar orbiter mission to Mercury (entitled MIRROR). On board would be a CD-array IR spectrometer and five l-kg ball bearings, each consisting of different rare metals, and launched, carefully of course once the spacecraft is in orbit, near the poles on the dark side (low background). When they hit, generating artificial "meteorite impacts," the IR spectrometer would measure the spectrum of the flash, and presto (sort of, making some assumptions), this measurement will be used to determine the amount of ice present in the volume vaporized at the two strike sites. Question: Why not fly a tried-and-true gamma ray spectrometer of comparable weight to create a low-resolution map of near-surface ice deposits? This suggestion may show my geochemical bias, but the idea has been discussed for some time. Answer: Yeah, but would it be as much fun as observing the results of the first ball-bearing bowling (the Editor's terminology) from space?

Future Issues

Upcoming issues will focus on groundbased observations of Mercury's atmosphere, details of proposed polar caps, and updates on the status of Mercury proposals selected for study in the Discovery program. If you would like to contribute or suggest a topic for a future issue, please contact the editor or one of the co-editors. Send contributions or requests to the editor at the following address: Pamela Clark, c/o Rita Clark, Code 691.0, NASA Goddard Space Flight Center, Greenbelt MD 20771.

Organizational Information