

**FROM COPERNICUS TO NEWTON TO EINSTEIN: TOWARD A DYNAMICAL UNDERSTANDING OF THE SOLAR SYSTEM.** Maria T. Zuber<sup>1</sup>, David E. Smith<sup>1</sup>, Erwan Mazarico<sup>2</sup>, Jonathan I. Lunine<sup>3</sup>, Gregory A. Neumann<sup>2</sup>, Frank G. Lemoine<sup>2</sup>, Antonio Genova<sup>1,2</sup>, Sander J. Goossens<sup>4,2</sup>, Xiaoli Sun<sup>2</sup>. <sup>1</sup>Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02129-4307, USA ([zuber@mit.edu](mailto:zuber@mit.edu)); <sup>2</sup>NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; <sup>3</sup>Dept. of Astronomy, Cornell University, Ithaca, NY 14853 USA; <sup>4</sup>CRESST, Univ. of Maryland, Baltimore County, Baltimore, MD 21250, USA.

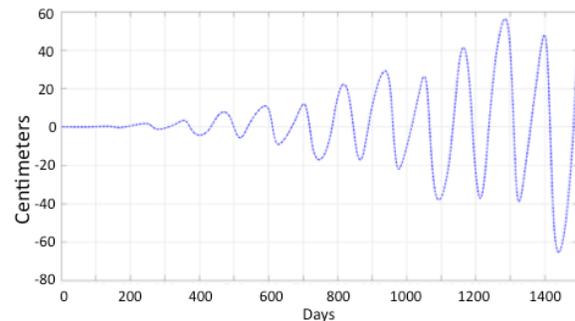
**Introduction:** It has been five centuries since it was established that the Sun was at the center of our solar system [1], three centuries since the basic laws that govern our solar system were formulated [2], and one century since those laws were modified to include relativistic effects [3] to bring us to our present understanding of how our solar system works. What new insights will the next 35 years bring? At the heart of our planetary system is the Sun that controls our planetary destiny and which is slowly but inexorably converting hydrogen into helium and slowly losing mass.

Measurements that could confirm the fundamental processes that govern our solar system are approaching the realm of possibility. Accurate monitoring of the motions of the planets about the Sun will answer certain basic questions, some which are essentially theoretical, about the evolving nature of individual planets, and the processes that are changing our Sun.

**Measuring the Solar System:** If we are able to accurately measure the distances of the planets with respect to each other over decadal timescales, we will have the data needed to understand their smallest motions and, by implication, the forces that are controlling their movement with greater accuracy. All solar system bodies are responding to the primary force of gravity, particularly that of the Sun, the gravitational interaction between them, as well as many other small forces. Monitoring of their motions enables us to estimate the forces that cause them; and central to everything is the Sun. Its gravity controls planetary orbits, its internal nuclear processes and expulsion of material in the solar wind reduce its gravitational mass that leads to an expected expansion of the solar system.

The magnitudes of many of these forces and their effects on the planets are small, but in some cases accumulate with time and in others introduce periodic signals of known frequency, enabling their recovery. For the fundamental scaling of the solar system the product of the gravitational constant,  $G$ , and the solar mass,  $M$ , is the principal term and the possibility that both parameters are changing is a well-known question. If we assume that the more recent estimates of the change in  $G$  [4, 5] suggest it is of order  $10^{-12}$  to  $10^{-13}/\text{yr}$  [8] and the change in  $M$  due to the conversion of hydrogen to helium in the solar interior [6] and the emission of protons in the solar wind [7] is also of order  $10^{-13}/\text{yr}$ , then the implied change in the distance of Earth from the Sun is several centimeters per year, which will accumulate with the square of time,  $t^2$ .

Although neither the change in  $G$  or  $M$  have actually been measured, the consequences of such changes are important. Today there is no fully understood reason why  $G$  would not be a constant, and a change in  $M$  is inferred from nuclear reactions taking place in the solar interior together with measurements of the flux of solar wind by spacecraft in Earth orbit. There is also the possibility that the change in  $M$  is not constant. Fig. 1 shows the predicted change in distance between Earth and Mercury over 4 years between March 2011 and April 2015 as a result of a change in the solar  $GM$  of  $10^{-13}/\text{yr}$  [8]. The observed change might be smaller as some compensation in the orbit may occur. The oscillation is the synodic orbital motion of Mercury with respect to Earth and amplitude steadily increases as the separation between Mercury and the Earth increases.



**Figure 1.** Predicted direct effect due to changes in solar  $GM$  in the distance between Earth and Mercury over the 4-year period that the MESSENGER spacecraft orbited Mercury, March 2011 to April 2015 [8].

Although the changes shown in Fig. 1 are small, they are measurable today as has been demonstrated by Lunar Laser Ranging [9], the LLCD [10] on the LADEE mission to the Moon, and by an asynchronous transponder experiment [11] between the Mercury Laser Altimeter (MLA) on MESSENGER and Earth. In the latter experiment range was measured to 20 cm over a distance of  $24 \times 10^6$  km, where the limiting factor was the 10-cm range accuracy of MLA.

But the real strength of the concept comes from the multiple combinations of baselines between many planets, effectively forming a grid that connects all the planets together into a single network. Each baseline provides a constraint on the solar system and the forces involved. A 5-planet network, for example, provides 24 baselines that contribute to a very robust solution.

A planetary dynamics network contributes to every aspect of solar system science. Table 1 is a brief list of the science and measurements that we expect will be obtainable after several years of observations. One of

Loss of solar mass by internal nuclear reactions and solar wind
Change in the gravitational constant, $G$
Test of equivalence principle
Expansion of the solar system
Lense-Thirring precession of reference frame
Relativistic parameters, beta, gamma
Gravitational flattening of the Sun, $J_2$
Precession, nutation and rotation of host planets
Obliquity, tides, moment of inertia of host planets
Low degree gravity, seasonal change on host planets
Inferences on interior structure, sun and host planets
Orbits of host planets/bodies

**Table 1.** List of some of the science measurements and parameters that will be possible with a planetary-scale laser ranging network.

the important solar parameters is the gravitational flattening,  $J_2$ , that can provide information about the radial distribution of mass within the Sun, observable in the motions of the inner planets but almost indistinguishable from the relativistic Lense-Thirring effect.

Gravitational flattening provides information about the radial density distribution within the Sun. At present, there are two methods of estimating solar flattening: planetary dynamics and helioseismology. The former is derived from planetary perturbations, principally Mercury, and the latter from observations of the rotation of the outer layers of the Sun. Table 2 summarizes recent estimates for the sun's  $J_2$ .

Source	Solar $J_2$ , $10^{-7}$	Reference
Dynamics	1.96 (2.11 $\pm$ 0.7)*	DE430, DE431, Folkner et al., 2014
Dynamics	2.13 (2.40 $\pm$ 0.2)*	MESSENGER, Verma et al., 2013
Dynamics	2.24 $\pm$ 0.1	MESSENGER, Genova et al., 2016
Helioseismology	2.20	Mercheri, et al., 2004
Helioseismology	2.206	Roxburgh, 2001
Helioseismology	2.22 $\pm$ 0.06	Amstrong and Kuhn, 1999
Helioseismology	2.22	Paterno et al., 1996
Helioseismology	2.18	Pijpers, 1998

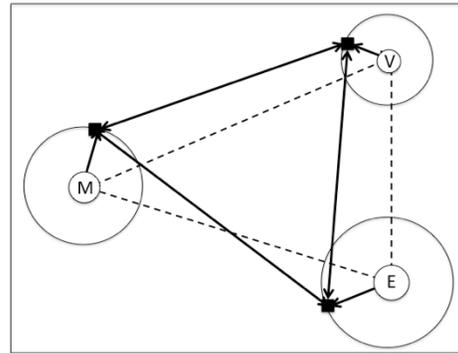
(\*) Prior to a reduction of 7% to account for Lense-Thirring effect

**Table 2.** Recent values for the solar flattening,  $J_2$ .

It is conceivable that the solar  $J_2$  is changing on an 11-year period with the solar cycle and a planetary geodetic network would be able to detect it. This would indicate subtle changes in mass distribution in the solar interior.

**Trilogy, A Proposed First Step:** Geodetic / geophysical spacecraft are placed in orbit about several planets or major solar system bodies; *Trilogy* [12] is an example of an initial concept that would place spacecraft in orbit about Earth (or Moon), Mars and Venus. The distances between the spacecraft are measured at the few centimeter level regularly over a period of 5 to

10 years from which the motion of the center of mass of the planets are inferred and  $G$ ,  $G\text{-dot}$ ,  $GM$  of the Sun, etc. are estimated. Fig. 2 shows the *Trilogy* configuration of planets and spacecraft. A possible alternative to using spacecraft could be landers on the Moon, or Mars, though dynamical perturbations at the planetary surface would need to be considered.



**Figure 2.** Trilogy concept with Earth, Mars & Venus.

**Technology readiness:** Measurements over planetary distances have been routine for decades at microwave frequencies, but such technology requires large antennae on the ground and on the spacecraft. Laser tracking and ranging over planetary distances has been demonstrated over the last decade and the telescopic instrumentation is smaller as, for example, laser altimeters that have operated at planets for years, with the laser altimeter (LOLA) on LRO continuing to operate in lunar orbit after nearly 8 years [13]. *Trilogy* envisages laser ranging terminals on small spacecraft, possibly cubesats, that can make range and/or range-rate measurements over several astronomical units at sub- $\mu$ s precision. The required technology is here today. Let's do it!

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