MEASURING SOLAR MASS LOSS AND INTERNAL STRUCTURE FROM MONITORING THE ORBITS OF THE PLANETS. Maria T. Zuber and David E. Smith. Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02129-4307, USA (zuber@mit.edu).

Introduction: The Sun is powered by the conversion of hydrogen into helium through the process of nuclear fusion. This reaction results in a decrease in the Sun’s mass, and in the release of energy through electromagnetic radiation and the solar wind [1]. The continued, steady loss of mass during the Sun’s evolution on the main sequence results in reduced a gravitational attraction and expansion of the orbits of the planets. These changes are small but are coming into the realm of possible measurement. Here we begin to consider the magnitude of the effect, what it would take to measure it, and what might be learned from planetary orbit changes about the structure and dynamics of the Sun.

Solar mass loss: In relatively low-mass stars like the Sun, the proton-proton reaction:

\[ 4 \text{H} \rightarrow 4\text{He} + 2e^+ + 2\nu_e + 2\gamma \]  

(1)

is the dominant way that hydrogen fuses into helium. Equation (1) indicates that positrons (e⁺), electron neutrinos (νₑ) and gamma rays (γ) are also produced in this reaction. A helium atom has about 0.7% less mass than four hydrogen atoms and it is this mass differential that is converted to energy via \(E = mc^2\). We consider the mechanisms for the loss of mass from the Sun due to electromagnetic radiation [2] and the solar wind [3].

From the observed solar flux the Sun emits 3.845x10^{33} ergs s⁻¹ [4], corresponding to a mass loss of 4.301×10^⁸ kg s⁻¹. The mass loss in one year is 1.3572×10^₁⁷ kg y⁻¹ and the fractional mass loss with respect to a solar mass is 0.068x10⁻¹² y⁻¹.

Protons constitute the primary component of the solar wind. For this estimate we multiply the proton mass of 1.67x10⁻²⁸ kg by the total flux over a unit sphere of radius 1 AU, which is 8.4x10³⁵ s⁻¹. Then each second Sun loses 1.41x10⁹ kg s⁻¹, the mass loss in one year is 4.44x10¹⁶ kg y⁻¹, and the fractional mass loss with respect to a solar mass is 0.022x10⁻¹² y⁻¹.

Note that these effects are of comparable magnitude.

The change in planetary orbits: The loss of mass from the Sun results in its decreased gravitational attraction of the planets. For example, in response to the solar mass loss calculated above, the orbit of Earth is expected to recede from the Sun about 2 cm y⁻¹. This is about half the yearly recession rate of the Moon from Earth, 3.8 cm y⁻¹ [5], which is measured routinely by Lunar Laser Ranging (LLR).

The magnitude of the change in Earth’s orbit due to solar mass loss is thus small, but within the realm of possibility with regard to measurement. Key in the ability to measure the rate of change of the Moon’s distance from Earth is repeated, high-precision measurements. The recession of the planets from the Sun also accumulates, over the square of time, \(r^2\). While a time series as long as exists for LLR isn’t practically feasible, measurements along many baselines – between planets – can conceivably add strength to solutions.

Making such measurements will require that all relevant physical effects or parameters have uncertainties no worse than the required measurement.

Job 1: Addressing uncertainties in \(GM\): 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. Recent estimates of the change in \(G\) [6, 7] suggest it is of order 10⁻¹² to 10⁻¹³ y⁻¹, so comparable to the change in \(M\) due to electromagnetic radiation and the emission of protons in the solar wind.

Although neither the change in \(G\) or \(M\) have actually been measured, the consequences of such changes are important. Today there is no well 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.

The possibility that \(G\) may not be constant complicates the ability to measure the change in \(M\). 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 y⁻¹ [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.

\[ \begin{align*}
\text{Centimeters} &= \begin{cases}
0 & \text{Days} = 0 \\
5 & \text{Days} = 100 \\
10 & \text{Days} = 200 \\
15 & \text{Days} = 300 \\
20 & \text{Days} = 400 \\
25 & \text{Days} = 500 \\
30 & \text{Days} = 600 \\
35 & \text{Days} = 700 \\
40 & \text{Days} = 800 \\
45 & \text{Days} = 900 \\
50 & \text{Days} = 1000 \\
55 & \text{Days} = 1100 \\
60 & \text{Days} = 1200 \\
65 & \text{Days} = 1300 \\
70 & \text{Days} = 1400 \\
\end{cases}
\end{align*} \]

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 [3], the LLCD [9] on the LADEE mission to the Moon, and by an asynchronous transponder experiment [10] 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.

There are ways that a temporal change in $G$ (aka $\dot{G}/G_0$) can be distinguished from that of $M$. Because the Moon’s orbit around Earth is not affected by solar mass loss, LLR measurements, if improved in accuracy, may be useful. Alternatively, a geodetic measurement mission [e.g., 11], would be able to limit $\dot{G}/G_0$ to parts in $10^{14}$ if implemented with drag-free design.

Measurements between planets would also enable measurement of 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 1 summarizes recent estimates for the Sun’s $J_2$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Solar $J_2$, $10^{-7}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamics</td>
<td>1.96 ($2.11 \pm 0.7)^a$</td>
<td>DE430, DE431,Follmer et al., 2014</td>
</tr>
<tr>
<td>Dynamics</td>
<td>2.13 ($2.40 \pm 0.2)^a$</td>
<td>MESSENGER, Verma et al., 2013</td>
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<tr>
<td>Dynamics</td>
<td>2.24 $\pm 0.1$</td>
<td>MESSENGER, Genova et al., 2016</td>
</tr>
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<td>Helioseismology</td>
<td>2.20</td>
<td>Mercheri, et al., 2004</td>
</tr>
<tr>
<td>Helioseismology</td>
<td>2.26</td>
<td>Rood, 2001</td>
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<tr>
<td>Helioseismology</td>
<td>2.22 $\pm 0.06$</td>
<td>Armstrong and Kuhn, 1999</td>
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<td>Helioseismology</td>
<td>2.22</td>
<td>Falerno et al., 1996</td>
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<tr>
<td>Helioseismology</td>
<td>2.18</td>
<td>Pipers, 1998</td>
</tr>
</tbody>
</table>

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

Table 1. 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 this parameter is conceivably detectable. This would indicate subtle changes in mass distribution in the solar interior.

Final thoughts: Improvements in laser ranging technology open the possibility of measurements relevant to the structure and dynamics of the Sun. Such measurements are within the realm of possibility of current technology. Analysis is required to understand uncertainties and how to disentangle the phenomena of interest from competing effects.