LUNAR LOVE NUMBERS AND THE DEEP LUNAR INTERIOR. J. G. Williams, D. H. Boggs, J. T. Ratcliff and J. O. Dickey, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109 (e-mail James.G.Williams@jpl.nasa.gov)).

Introduction: Information on the deep lunar interior is elusive. Evidence for a small core comes from the moment of inertia [1] coupled with interior models such as [2, 3, 4], induced magnetic dipole moment [5], and lunar rotation [6]. Dissipation associated with the rotation indicates that there is a fluid core. It is not known whether there is a solid inner core. The zone above the core and below the region of deep moonquakes strongly damps seismic waves [7, 8, 9]. This region may also be the source of strong tidal damping [6].

The three-dimensional rotation of the Moon is sensitive to tidal dissipation, dissipation due to relative motion at the fluid-core/solid-mantle boundary, and tidal Love number k_2 [6], as well as flattening of the core-mantle boundary [10]. There is a long-standing problem with understanding Lunar Laser Ranging (LLR) determinations of the Love number. The value is larger than simple interior model predict [11]. This could be due to bias from another effect, core-mantle boundary flattening, or it could indicate that lunar models are too simple [11]. Recent solutions include a flattening-related parameter in addition to the Love number.

Love Number Determinations: Three decades of Lunar Laser Ranging (LLR) data are analyzed using a weighted least-squares approach. The lunar solution parameters include dissipation at the fluid-core/solid-mantle boundary, tidal dissipation terms, Love number k_2, a correction to the constant term in the tilt of the equator to the ecliptic which is meant to compensate core-mantle boundary flattening, and displacement Love numbers h_2 and l_2. The LLR solution value of $k_2 = 0.0266 \pm 0.0027$ is sensed through variations of three-dimensional rotation. There is a concordant spacecraft determination of the lunar Love number of $k_2 = 0.026 \pm 0.003$ which relies on variation of the gravity field [12].

Model Love Numbers: Given a model for the radial distribution of the Moon's density and seismic P- and S-wave velocities the Love numbers can be calculated. Lunar models are based on the mean density, moment of inertia, seismic speeds, and geochemical considerations.

Seismometers left on the Moon during the Apollo missions detected moonquakes and impacts. This data set has been analyzed to obtain the radial distribution of P- and S-wave speeds [8, 9, 13]. The Nakamura [9] and Goins, Dainty and Toksoz [8] inversions of the seismic data generally agree for the upper lunar mantle, but diverge more widely for the deeper regions. Nakamura [9] called the depth range of 500-1000 km the middle mantle. For this middle mantle the S-wave speeds of Goins et al. [8] are smaller than Nakamura's while those of Khan, Mosegaard and Rasmussen [13] are larger. Below the region of deep moonquakes and above the core there is a zone of higher seismic attenuation. The above three seismic inversions do not extend into the attenuation zone or core.

A sequence of lunar models have been published by Kuskov and Kronrod [2, 3, 14] and Kuskov, Kronrod, and Hood [4]. While the model distributions are not determined exactly, they give a limited spread of plausible distributions. The seismic data do not constrain the attenuation zone and core so a wider range of possibilities exist for these deepest regions.

For the first set of Love number computations, the seismic properties of the middle mantle are extended down to the core. Two extremes for cores are considered: one mainly liquid, the other a thin fluid shell over a thick solid inner core. Core compositions of liquid and solid iron and liquid Fe-FeS eutectic are considered. For several Kuskov and Kronrod models k_2 ranged from 0.021-0.022 for trivial sized cores, 0.022-0.023 for iron cores (liquid or solid) of about 330 km radius, and 0.023-0.024 for fluid Fe-FeS eutectic cores of 430 km size. A 430 km core is larger than the 374 km 1-σ upper bound from the LLR dissipation analysis [6]. All of these model values are less than the two observationally determined Love numbers.

If the model seismic speeds of Kuskov and Kronrod are replaced with Nakamura's speeds, and the middle mantle speeds are extended down to a 330 km iron core, then $k_2 = 0.022$. When computing a model Love number k_2 the sensitivity to the S-wave velocity is an order-of-magnitude larger than the sensitivity to the P-wave velocity. Lower speeds are associated with larger Love numbers. Using Nakamura's lower limits for speeds increases k_2 to 0.023. The smaller middle mantle S-wave speeds of Goins et al. would increase the model Love numbers over those of Nakamura (see [11]) and the higher speeds of Khan et al. would decrease the model Love numbers.

To explain its high seismic damping Nakamura [7] proposed that the attenuation zone was a partial melt. A partial melt would also have decreased seismic speeds which would increase the model Love numbers [11]. Lowering the S-wave speed by 1 km/sec between 1000 km depth and the core increases the model k_2 by 0.002. From free oscillation data Khan and Mosegaard [15] found an S-wave speed decrease in this region.

Summary: To bring the model values of the Love number k_2 up to the two observationally determined values of about 0.026 it is necessary to either decrease the middle mantle speeds from those models and

Nakamura's analysis, or to make the attenuation zone a low velocity layer, or to increase core radius above presently accepted sizes. The uncertainty of the observationally determined values is still about 10% which is uncomfortably large compared to the differences from models, but there are two independent and concordant determinations and all model values are less. There is need for improved uncertainty in the determinations and the lunar interior models may need to become more complex.

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