

Evolution model of the lunar orbit with tidal resonance of normal modes in the early Earth's ocean

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According to the Giant impact hypothesis when the Moon was formed very near the Earth (Hartman & Davis, 1975), the tidal force would extensively generate dynamical interaction between the early Earth and Moon. The Lunar orbit evolution is estimated using the perturbation theory of gravitational potential (e.g. MacDonald, 1964, Kaula, 1964, and Lambeck, 1977). Although there are many studies suggested the orbit evolution backward depending on time the present to the past, the initial period evolution of the Earth-Moon system is obscure. The energy dissipation is an important factor to study the evolution of the Earth-Moon system, it is estimated by the deformation of the Earth. In general, the complicated response of the ocean has been calculated using numerical simulation (e.g. Abe and Ooe, 2001). However, the dependency of the effects of the Earth's ocean response has not systematically been investigated for the early evolution. Since the early Earth after cooling of the magma ocean is considered to have been covered almost entirely by the seawater, the ocean tide could affect the early evolution of the Earth-Moon system as well as the solid Earth's tide. Although the potential of semi-diurnal tides (corresponding to spherical harmonics Y₂₂) was much larger in the ancient time, it would significantly be attenuated due to mechanical response of water motion (e.g. Hansen, 1982, Abe and Ooe, 2001). In this study, we adopt a model of the constant-depth ocean with bottom friction as the early Earth's ocean (e.g. Abe et al., 1997). The basic equations of seawater motion are well known as the Laplace's tidal equations (LTE). The LTE of the free oscillation can numerically be solved to give eigenfrequencies and eigenfunctions in function of the ocean depth and the rotation rate of the Earth (Longuet-Higgins, 1968). Based on these normal modes, we obtained a semi-analytical response function with bottom friction against the tidal force of the Moon. This response function includes various parameters: the Earth's rotation rate, the ocean depth, the bottom friction coefficient, the Love number and load Love number of the Earth's deformation. The response function in the present study shows good agreement with the numerical simulation result of the tidal torque response of Y₂₂ (Abe et al., 1997). Applying the response function of the semidiurnal tide, it is found that resonance could sometimes occur for higher-degree normal modes for gravity waves in the early Earth's ocean, associated with rapid increase in the semi-major axis of the lunar orbit. This temporal change might trigger a rapid decrease in the Moon's rotation rate and also rapid increase in tidal heating of the Moon. It is also implied that the possible resonance of diurnal tide could occur as planetary wave, the effect of which is smaller than that of semidiurnal tidal resonance. We will discuss possible effects on the coevolution of the Earth-Moon system due to the tidal response in the early Earth's ocean.

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