惑星軌道の永年変化に対する海洋潮汐波の回転効果
Effect of rotating ocean waves on tidal evolution of a planet-satellite system

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The ocean tide observed on the Earth is mainly driven by gravitational force exerted by the moon on the ocean and the centrifugal force associated with Earth's revolution (i.e., revolution around the common center of gravity of the moon and the Earth). The ocean tide rises and falls the sea level in a periodic manner, thus generating oscillatory flow of sea water at the global scale, called tidal current. It is broadly accepted that the friction between tidal current and the sea floor causes dissipation of the mechanical energy of the Earth-moon system at a rate of several terawatts. Due to this energy dissipation, the Earth’s rotation rate becomes slow gradually, and the decrease in its angular momentum is transferred to the moon. As a consequence of the angular momentum transfer, the orbital length radius of the moon has been getting longer at a rate of 3.8 cm/year, as was confirmed by the laser range finding experiment using the reflector installed on the moon.

In the present work, we consider the contribution of angular momentum carried by the "coastal Kelvin wave" to the secular variation both in the Earth's rotation and the moon's orbit radius. Here, the coastal Kelvin wave is a tidal wave in the ocean that balances the Earth' Coriolis force against a topographic boundary such as a coastline or a submarine basin. It is known that the coastal Kelvin wave rotates at the same cycle as the tide at the inner edge of the topographic boundary. An important feature of the coastal Kelvin wave is that it is non-dispersive, i.e., the phase speed of the wave crests is equal to the group speed of the wave energy for all frequencies. This means that it retains its shape as it moves in the alongshore direction over time. Furthermore, most coastal Kelvin waves in the northern (or southern) hemisphere are known to propagate in a counterclockwise (clockwise) direction, wherein the coastline plays a role of a wave guide. This fact implies that those rotary waves all contribute positively to the angular momentum vector with respect to the Earth's rotation axis. In particular, the contribution to the secular variation is likely to become much significant if the two celestial bodies (e.g., the Earth and moon) get much closer than now as it was billions of years ago, because the short distance between the two will amplify the difference in the tidal level associated with the Kelvin waves. So how can we describe the contribution of the Kelvin waves to the two-body's celestial dynamics?

To resolve the problem posed above, we have formulated the angular momentum of the rotary tidal waves as a function of the latitude and the Earth-moon distance. In our argument, the velocity of the sea water consisting the tidal waves was evaluated using the shallow-water wave equation; the equation is valid under the condition that both the radius of the submarine basin and the wavelength of the tidal wave are sufficiently longer than the mean depth of the sea. The obtained formula provides us with a threshold of the inter-planet distance below which the Kelvin waves will be relevant to the two-body's tidal evolution. Added to the above discussion, we have specifically considered the tidal evolution of the Earth-moon system immediately after the moon was born (about 4 billion years ago). In the very ancient times, the

Earth-moon distance was only about one tenth of the current one. We demonstrate that in such the situation, the angular momentum of the tidal current had a large effect on orbital change of the Earth-moon system. We also emphasize that formulation we have developed can apply to not only the Earth-moon system but to other planet-satellite systems as long as the planet holds liquid on the surface. It is thus hoped that the conclusion regarding the effect of rotating tidal waves on secular variation may open an avenue to new findings on the tidal evolution of general planet-satellite system.

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