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Lunar apex–antapex cratering asymmetry as an impactor recorder in the Earth–Moon system

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Abstract

The degree of apex–antapex cratering asymmetry of a synchronously rotating satellite primarily depends on the mean encounter velocity of impactors with respect to the planetary system and the orbital velocity of the satellite. This means that we can estimate the mean encounter velocity of impactors by observing the apex–antapex cratering asymmetry, if the relationship between these is known. To apply this technique to the Moon, we attempt to derive the relationship between the mean encounter velocity of impactors and the degree of the lunar cratering asymmetry as a function of time, considering the temporal variation in the lunar orbital velocity during the last 4.0 Gyr. We used the cratering asymmetry of Zahnle et al. [Zahnle, K., Schenk, P., Sobieszczyk, S. et al. Differential cratering of synchronously rotating satellites by ecliptic comets. Icarus 153, 111–129, 2001] to obtain the relationship. Applying this relationship enables us to estimate the impactor's velocity of the Earth–Moon system from an investigation of the spatial distribution of lunar craters. Furthermore, we re-evaluate the cratering asymmetry's influence on lunar cratering chronology.

Keywords: Cratering asymmetry; Impactor; Earth–Moon system; Near-Earth Objects; Cratering chronology

1. Introduction

The main source of impactors in the Earth–Moon system has been investigated from the size–frequency distribution of lunar craters over the last 4.0 Gyr (Werner et al., 2002; Strom et al., 2005). In this study, we present a novel technique for impactor investigation using the lunar apex–antapex cratering asymmetry due to synchronous rotation.

Synchronous rotation of a planetary satellite should generate a spatial variation in the crater production rate on its surface (Shoemaker and Wolfe, 1982; Horedt and Neukum, 1984; Zahnle et al., 1998, 2001, 2003; Le Feuvre and Wieczorek, 2005, 2006; Gallant and Gladman, 2006). The maximum production rate at the apex of the orbital motion of the satellite decreases with an increase in angular distance from the apex and becomes the minimum at the antapex. The degree of the apex–antapex cratering asymmetry primarily depends on the mean encounter velocity of impactors with respect to the planetary system and the orbital velocity of the satellite (Wood, 1973; Shoemaker and Wolfe, 1982; Horedt and Neukum, 1984; Zahnle et al., 1998, 2001, 2003). The ratio of the maximum rate to the minimum value increases with the decrease of the encounter velocity of impactors. This means that we can estimate the mean encounter velocity of impactors by observing the apex–antapex cratering asymmetry, if the relationship between these is known.

Morota and Furumoto (2003) verified the validity of this technique. From investigation of the spatial distribution for the Moon's rayed craters, they estimated the mean

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velocity of recent impactors in the Earth–Moon system to be about 15 km/s, corresponding to that of near-Earth asteroids (NEAs). This result is consistent with recent comparisons between the size–frequency distributions for NEAs and lunar craters; the shape of the size distribution of current NEAs is similar to that of lunar craters (Werner et al., 2002).

The Terrain Camera (TC) installed on SELENE, a Japanese lunar explorer to be launched in 2007, will take surface images of the whole Moon with a nominal spatial resolution of 10 m/pixel (Haruyama et al., 2000, 2003, 2006; Ohtake et al., 2000). The extensive high-resolution images will be used to identify relative and absolute ages for individual craters over the whole Moon by crater counting, and the morphologic and stratigraphic interpretations. We will try to detect possible changes of impactor origin by investigating cratering asymmetry for each geologic period. Before that, however, it is necessary to understand the relationship between the impactor's velocity and the cratering asymmetry.

In this paper, we propose to derive the relationship between the lunar apex–antapex cratering asymmetry and the mean encounter velocity of impactors as a function of time, considering the temporal variation in the lunar orbital velocity during the last 4.0 Gyr.

2. Lunar cratering asymmetry and impactor's velocity

The apex–antapex cratering asymmetry was formulated by analytical studies and numerical simulations (Shoemaker and Wolfe, 1982; Horedt and Neukum, 1984; Zahnle et al., 1998, 2001). Zahnle et al. (2001) gave the cratering rate as a function of the angular distance β from the apex as follows:

$$\Gamma = \bar{\Gamma}\left(1 + \frac{v_{\mathrm{orb}}}{\sqrt{2v_{\mathrm{orb}}^2 + v_\infty^2}}\cos\beta\right)^{2.0-1.4b}, \tag{1}$$

where $\bar{\Gamma}$ is the cratering rate at $\beta = 90$, v_{orb} and v_∞ are the orbital velocity of the satellite and the encounter velocity of impactors in the planetary frame at infinity, and b is the exponent of the mass-frequency distribution of the impactors. From Eq. (1), the ratio of the cratering rate at the apex to that at the antapex is

$$\gamma = \Gamma_{\mathrm{apex}}/\Gamma_{\mathrm{antapex}} = \left\{\left(1 + v_{\mathrm{orb}}\Big/\sqrt{2v_{\mathrm{orb}}^2 + v_\infty^2}\right)\Big/\left(1 - v_{\mathrm{orb}}\Big/\sqrt{2v_{\mathrm{orb}}^2 + v_\infty^2}\right)\right\}^{2.0-1.4b}. \tag{2}$$

The orbital velocity of the Moon has probably varied since the formation of the Moon in conjunction with an increase in the Earth–Moon distance. To estimate the degree of the lunar apex–antapex cratering asymmetry as a function of time from Eq. (2), we assume the computed result of lunar orbital evolution by Abe and Ooe (2001) (Fig. 1). They evaluated the tidal evolution of the Earth–Moon system

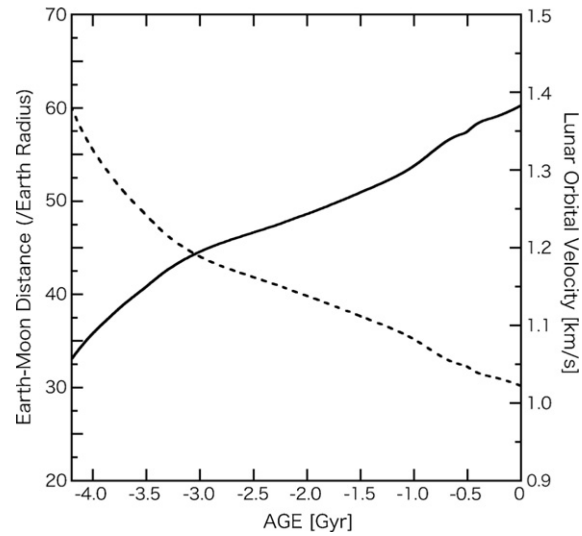

Fig. 1. Lunar orbital evolution. Solid curve indicates the Earth–Moon distance calculated by Abe and Ooe (2001), and dashed curve indicates the lunar orbital velocity calculated from the lunar orbital evolution.

by estimating the change in dynamic responses of ocean and solid Earth to the lunar and solar tidal force during a geologic time. As a result, they developed an evolution model of the Earth–Moon distance over 4.0 Gyr. Substituting lunar orbital velocity calculated from the orbital evolution model for v_{orb} in Eq. (2), we can derive the degree of cratering asymmetry as a function of time.

We also assume $b = -0.53$ implied by the crater size–frequency distribution $N \propto D^{-1.8}$, where N is the cumulative number of craters and D is the crater diameter. The exponent of -1.8 is well fitted for a size distribution of post-late heavy bombardment craters larger than 4 km in diameter (e.g., Baldwin, 1971; Melosh, 1989; Namiki and Honda, 2003). In contrast, the late heavy bombardment population has a complex size distribution: its slope varies significantly with crater size range (Strom et al., 2005). Therefore, the cratering asymmetry derived in this study can be applied only to post-late heavy bombardment cratering.

The apex/antapex ratio of cratering rates is calculated for various encounter velocities of impactors v_∞. Fig. 2 displays the calculated result.

3. Discussion

Fig. 2 enables us to estimate the impactor's velocity from investigating the spatial distribution of craters. For example, Morota and Furumoto (2003) identified rayed craters, mainly on the far side, from Clementine UVVIS images and estimated the apex/antapex ratio of rayed craters to be 1.50 ± 0.09. The gray zone in Fig. 2 indicates the observed asymmetry. The apex/antapex ratio corresponds to an impactor velocity of about 15 km/s. Furthermore, it is possible to infer the origin of impactors from the velocity because the encounter velocities differ among the impactors. The mean encounter velocity of near-Earth asteroids