PARTICLES FROM EPHEMERAL PLUME ACTIVITIES OF ENCELADUS DEPOSIT ON SATURNIAN SATELLITES.

Naoyuki Hirata[1], Hideaki Miyamoto[1], and Adam P. Showman[2], [1]The University Museum, The University of Tokyo, Hongo, Tokyo 113-0033 Japan, hirata@um.u-tokyo.ac.jp. [2]Department of Planetary Science, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.

The geologically active south pole of Enceladus generates a plume of micron-sized particles [1], which is considered to be the primary source of Saturn's tenuous E ring. The ring particles extend from the orbit of Mimas to at least as far as the orbit of Titan [2]. Mid-sized satellites in the E ring, such as Tethys and Dione, show almost bimodal distributions of albedo [3] and VIMS spectra [4], which is explained by differential accumulation of E-ring material on their surfaces [5,6,7]. However, no depositional features have been reported on satellites in the E-ring region except for those on Enceladus (e.g., buried craters) [8]. We thoroughly examine all high-resolution images obtained by the Cassini spacecraft to the end of Nov. 2012 and find that possible depositional features ubiquitously exist on small satellites in the E ring region. The best examples are found on Helene because it is the most extensively imaged small satellite in the E ring.

Helene shows a bimodal appearance contrasting the smooth-looking leading hemisphere to the heavily cratered, sub-Saturn side of the trailing hemisphere, which has a crater density 10 times larger than that of the leading hemisphere (Fig. 1). We study 437 high-resolution images of Helene (500 m/pixel or better) obtained by the Cassini spacecraft through 7 flybys between 2006 and 2011 and find that Helene has numerous, sharply curved gully-like depressions (hereafter streaky depressions). Streaky depressions exist only on slopes on the leading hemisphere typically as a group sharing their directions. No streaky depressions are found on the trailing hemisphere (Fig. 1). We develop a numerical shape model to calculate the local gravitational gradients for the entire surface of Helene, and we critically compare these gradients to the distribution of streaky features (Fig. 2). We find that streaky depressions exist only on slopes and strictly follow the local gravitational slopes, which indicates that the streaky depressions are results of gravity-induced mass movements.

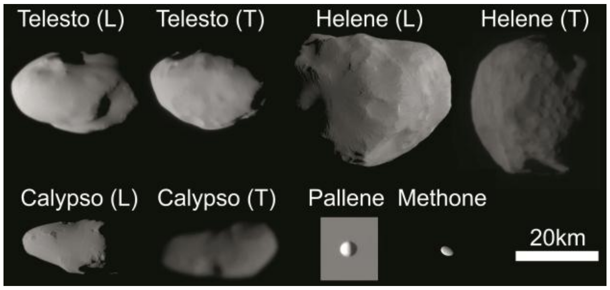

Fig. 1. Small satellites located at the E ring region shown in the same scales. (L) and (T) mean that the image is the leading and the trailing side, respectively (N168712110, N1563643679, N1630076968, N1514163666, N1644754662, N1506184171, N1665947247, N00189072).

We consider that the leading hemisphere of Helene is generally covered by these particles because (1) all streaky depressions exist only on the leading hemisphere; (2) almost no small craters can be identified on the leading hemisphere; and (3) the shapes of large craters are flattened, which indicates that depositions of fine particles have modified or erased craters on the leading hemisphere. We statistically study the crater distributions on Helene, which supports the view that the small craters on the leading hemisphere are preferentially buried, possibly by fine particles. The VIMS of the leading hemisphere of Helene are similar to that of the E ring [4], which indicates that these particles come from the E ring.

In addition, We find similar deposits on other small satellites in the E ring, Telesto, Calypso, Pallene, and Methone, where higher brightness (i.e., presumably higher densities) of the ring are reported [2]; For example, craters on Telesto and Calypso generally exhibit obscured shapes with unclear rims (or sometimes they are entirely erased) similar to those on the leading hemisphere of Helene. In fact, even large (>10 km in diameter) craters on Telesto and Calypso appear to be buried just as small craters are on Helene. Also, Calypso exhibits streaky depressions (Fig. 1), which appear to follow local gravitational slope. Their spectral similarities with the E ring [9] support the view that, as with Helene, E-ring material accumulated on these satellites into thick deposits. Moreover, high-resolution images of Pallene and Methone (Fig. 1) indicate these satellites have a featureless spherical shape, which is unusual for a body of a few km in radius. These smooth, spherical or ellipsoidal shapes are also explained by the possible accumulation of E-ring material on their surfaces, as such material can cover the original irregular topography.

The high crater density on the trailing hemisphere indicates that Helene is basically an old object; based on the crater chronology of the Saturnian system [10]. On the other hand, we identify 5 craters of 200m diameter but no crater of more than 1km in diameter on the Helene's E ring deposit. If we adopt standard cratering-rate estimates for the outer solar system [10], the formational ages of the deposits are (1) younger

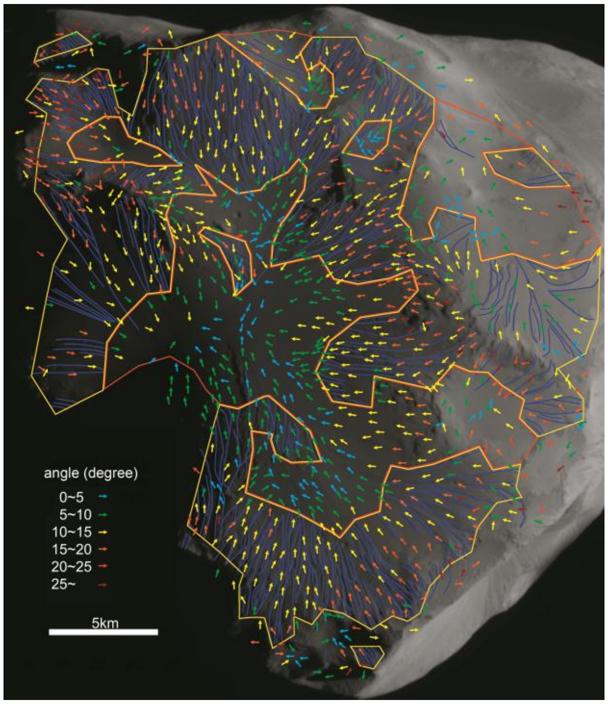

Fig. 2. The leading hemisphere of Helene (N1687120437) with arrows indicating the directions of the local gravity (color represents slopes). Blue lines indicate streaky depressions. The regions enclosed by yellow or red lines are the regions with and without streaky depressions, respectively. Note that streaky features exist only on steeper (> ~7 degree) and strictly follow the directions of surface gravity.

than 0.3-5My (if we assume the size–number distribution is like that inferred at Jupiter), (2) younger than 200-500My (if we assume that small objects obey a more nearly collisional distribution), (3) ~40My (if we assume that the heavily cratered regions on Helene, which have 100 craters per 1000km^2 larger than 1km in diameter, was formed more than 4 Gy and that the cratering rate is constant for its life time), or (4) ~50My (if we assume the crater distributions of Dione, whose Trojan satellites include Helene). Therefore, we consider that the best estimates for deposit ages are several tens of million years or younger. The crater size-frequency distribution of the trailing hemisphere of Telesto, only where high-resolution images are obtained, is similar to that of the leading hemisphere of Helene.

We estimate that the thickness of the E ring deposits on Helene is between 10 to 300m. On Telesto and Calypso, the minimum size of craters is also about 3km in diameter, which again indicates deposit thicknesses of hundreds of meters. On the other hand, the deposits on Tethys and Dione are probably quite thin but non-zero deposits of the E-ring particles. Thus, here we assume the E-ring particles are likely deposited widely on Tethys and Dione but their thicknesses are from 1 mm to 1 m. Overall, the estimated total amount of the E ring deposits on satellites in this region is in the range of $1.2x10^{12}$ to $8.7x10^{12}$ m^3. The origin of the E ring particles is known to be Enceladus, whose mass of solid material per unit time escaping from Enceladus is considered to be most likely ~5 kg/s [11,12]. The fate of the E ring particles after escaping from Enceladus is still a matter of debate, however, the lost rate due to collisions to satellites could be so large because its lifetime is considered to be quite short, as well as ~20 years [13]. Thus we assume that the collision to satellites can be a dominant process of particle loss from the E ring. These arguments suggest that 10 to 100% of particles ejected from Enceladus would be lost by collisions to satellites, which corresponds to deposits of $3.15x10^{12}$ ~ $3.15x10^{11}$ m^3 in thickness, respectively, if we assume 500 kg/m^3 for the density of the deposits. At the current discharge rate of ~0.5 kg/sec, the total volume of the E ring deposits on satellites estimated above ($1.2x10^{12}$ to $8.7x10^{12}$ m^3) would accumulate in only ~4 to 300 My.

Interestingly, the endogenic activity of Enceladus is also considered to be short period due to the following reasons; (1) no geological evidence exists to support the large change in its radius, which can be expected if the current mass-loss rates have been maintained through Enceladus' lifetime [14], and (2) the deficiency in craters around the tiger stripes in the south-polar region implies an age younger than at most 100 My [10,14]. We note this estimated age coincides with our estimate of the formational age of the E ring deposits on Helene. Thus, there is the possibility that the accumulations of the E ring material on small satellites in this region begun at several My ago as a result of the initiation of cryovolcanism on the surface of Enceladus. This is consistent with arguments that the current energy output of Enceladus is difficult to sustain over solar-system history [15].

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