CRATER CHAINS ON THE MOON: RECORDS OF COMETS SPLIT BY THE EARTH'S TIDES?; H. J. Melosh and E. A. Whitaker, Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721.

The recent recognition [1] that nearly a dozen crater chains on Callisto may have been created by comets disrupted during passage inside Jupiter's roche limit has prompted us to search for crater chains on the Moon that may have been created by comets similarly disrupted by passage within the Earth's roche limit. We have located at least two candidate crater chains that are not obviously secondaries from any large crater or basin. Both chains are on the lunar nearside, as expected for comets split during a close pass by the Earth, and range in length from about 50 km for the well-known Davy chain to between 200 and 250 km for a chain near the crater Abulfeda. These chain lengths are in good agreement with predictions from a tidal splitting model. The existence of two crater chains on the moon implies a cometary flux similar to that indicated by crater chains on Callisto. If this flux has been uniform over the past 4×10^9 years, it predicts a comet impact flux two orders of magnitude greater than that estimated by Shoemaker et al. [2]. This may indicate that the crater chains were formed near the end of late heavy bombardment when the impact flux was much higher than at present, or alternatively that such crater chains are also made by asteroids passing within the roche limit. This last possibility would support the rubble-pile model of asteroids. The recurrence time between these splitting events is at least 10^4 years.

Table I summarizes information about the two chains we believe may be the products of tidally-split comets. Although the Davy chain is a relatively fresh, post-Imbrian chain [3], the Abulfeda chain is more degraded and is assigned an Imbrian age [3]. The disparity in the lengths of these chains might at first suggest that they do not have similar origins. However, a simple model for tidal splitting [1] that assumes a radial breakup at perigee shows that the length of the chain is a linear function of the parent size. Since the craters in the Abulfeda chain are roughly 5 times larger than those in the Davy chain, it is not unreasonable that the Abulfeda chain is roughly 5 times longer. The Moon is roughly 60 Earth radii (R_E) from the Earth, which is relatively much more distant than Ganymede and Callisto are from Jupiter (14.9 and 26.2 Jovian radii, respectively). The length of crater chains on the Moon created by objects splitting within the Earth's roche limit is thus very sensitive to the approach velocity, as low approach velocities allow a long time for the fragments to separate. Figure 1 shows that the length of a chain of fragments produced by a 1 km radius parent comet can vary between 600 and 8 km for approach velocities at infinity ranging from 1 to 30 km/sec and a passage within 1.5 R_E. Figure 2 shows the dependence of chain length on the distance of closest approach. The length of the chain thus

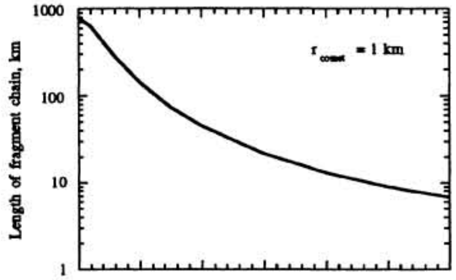

Fig. 1 Fragment chain length vs. approach velocity

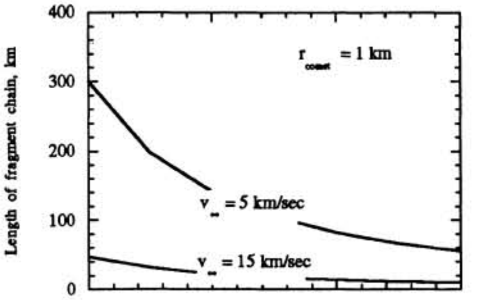

Fig. 2 Chain length vs. approach distance

provides very little constraint on the tidal splitting mechanism, since it is so sensitive to reasonable variations in the approach conditions.

The tidal stresses experienced by an object approaching within the Earth's roche limit are actually larger than those approaching Jupiter at a similar relative distance. Using a simple estimate of the tidal stress [4], σ_{tide} is given in terms of the comet density ρ, mass of the Earth M_E, radius of the comet r_c, and distance of approach R.

$$\sigma_{tide} \approx 0.15 \frac{\rho G M_E}{R^3} r_c^2 = 0.63 \frac{G \rho \overline{\rho}}{(R / R_E)^3} r_c^2$$

The second equation is written in terms of the planet's mean density $\overline{\rho}$, and it is clear that for approach at a given fraction of the radius of any planet, the tidal force is proportional to $\overline{\rho}$. Since the Earth's mean density is about 5 times that of Jupiter, the tidal forces on an object approaching to, say, 1.5 radii are correspondingly larger. The tidal stress on an Earth-approaching comet is thus about $\sigma_{tide} \approx 6.8 x 10^{-4}\ r_c^2 (\mathrm{km})$, where the stress is in bars. In spite of these relative larger stresses, the inferred strength of comets is still very small (measured in millibars for comets of a few km radius) and suggests a model for comets in which a few mechanically strong chunks are held together by self gravity alone.

Supposing that the two crater chains near Davy and Abulfeda are created by tidally split comets, a few inferences on the cometary flux may be deduced. From the ratio of the areas of a sphere enclosing the Moon's orbit and the Moon's disk, the observation of two crater chains on the moon implies about 4×10^5 split comets overall, assuming that the comets approach the Earth in random directions. Over 4×10^9 years, this suggests a recurrence interval of at least 10^4 years, assuming a constant flux with time. This is about 100 times longer than the inferred recurrence time for comet splitting events about Jupiter, using the same assumptions [1]. However, the area of Jupiter's roche limit-cross section is also about 100 times larger than the Earth's, so the observation of two crater chains on the Moon thus suggests about the same flux at Earth and Jupiter. Finally, if 4×10^5 comets passed between the Earth's surface and its roche limit, then a fraction of about 0.19 of these comets should have struck the Earth itself. Over 4×10^9 years this implies a cratering rate of about 2×10^{-5} cometary impacts per year, which is much larger than Shoemaker et al.'s [2] estimate of 10^{-7} per year for comets with diameters greater than 2.5 km. There are two possible (perhaps not competing) explanations of this discrepancy. First, this computation assumes a constant cratering rate. It may be that the lunar crater chains were emplaced during the end of heavy bombardment. This is plausible for the Abulfeda chain, but perhaps less likely for the post-Imbrian Davy chain. On the other hand, Shoemaker et al. [2] estimate an impact flux of 4×10^{-6} per year of asteroids greater than 1 km in diameter, which is still smaller than the flux estimated from the crater chains, but it may be that the poor statistics on crater chains yield a spuriously high flux. In this case, however, we would have to admit that *both* asteroids and comets can be tidally disrupted to produce crater chains, a speculation tending to support the rubble-pile model for asteroids.

Table I. Crater Chains on the Moon not Secondary to Craters or Basins

Name	Latitude	Longitude	Length, km	Crater Dia. Range, km	Number of Craters	LO frame
Davy	-10°	-9°	47	1-3	~23	IV-108-H2
Abulfeda	-15	15	200-260	5-13	~24	IV-89-H2

References [1] H. J. Melosh and P. Schenk, Nature **365**, 731-733 (1993). [2] E. M. Shoemaker, R. F. Wolfe and C. S. Shoemaker, Geol. Soc. Amer. Spec. Pap. **247**, 155-170 (1990). [3] D. E. Wilhelms and J. F. McCauley, USGS Map I-703 (1971). [4] J. V. Scotti and H. J. Melosh, Nature **365**, 733-735 (1993).