USING DOUBLET CRATERS ON CERES TO CONSTRAIN THE MAIN BELT BINARY ASTEROID POPULATION P. F. Wren[1] and R. A. Fevig[1], [1]Department of Space Studies, University of North Dakota, Clifford Hall Room 512, 4149 University Ave Stop 9008, Grand Forks, ND, 58202 paul.wren@und.edu

Introduction: A doublet is a pair of impact craters created by the same primary impact event [1]. Doublets have been observed on Earth, the Moon, Mercury, Venus, Mars [2,3,4,5,6,7,8], and now on Ceres.

Doublet crater formation. Originally, doublet crater formation was attributed to a single impactor broken up by either atmospheric disruption [9] or tidal forces [1,10], but further studies showed these processes could not result in sufficient separation to create the observed doublets [11,12]. It is now believed that well-separated binary asteroids are the source of doublet craters [12]. This makes doublets a source of evidence for the prevalence of binary asteroid systems.

Constraining binary asteroid populations. The percentage of asteroids in the near-earth population that are binary is fairly well established at 15%, and doublet craters on Mars, Earth, Venus, and the Moon have been used to confirm this value [2,18]. 144 binary asteroids have been identified in the main belt using ground-based and spacecraft observations [13], but smaller binary systems have likely gone undetected. The Dawn spacecraft at Ceres [14,15] has provided a large catalog of detailed images. Doublet craters on Ceres would provide evidence for the abundance of binary asteroid systems in the main belt, down to smaller diameters than previously possible.

Previous Pilot Study: Applying the methods described below, we studied a small sample area on Ceres covering approximately 28,000 km^2 [19]. Terrain was chosen near the large craters *Urvala* and *Yalode* for its low crater density, to minimize the number of randomly-adjacent impact craters [16]. The 80 craters ≥ 3 km resulted in 172 crater pairs separated by less than 20km. After initially identifying four candidate doublets, we have since selected two of these pairs as likely doublets (see Figures 1c and 1d) due to the presence of a possible septum in each pair.

Data and Methods: Inspired by Melosh, Ingram, and Bottke [8], we adopted a similar data collection and analysis approach. We expanded the pilot study area westward, increasing the total area by a factor of 15. The final study region is bounded by 110°E to 270°E and 10°N to 30°S, roughly 430,000 km^2. Using JMARS [19], we will count impact craters ≥ 3 km appearing in Dawn Framing Camera images from this region captured during the Low Altitude Mapping Orbit (LAMO) [17]. Craters separated by less than 20 kilometers will be considered potential doublets and evaluated using our scoring system. Points are added for similar erosion, as well as for possible ejecta lobes or a septum. Points are subtracted for superposition, or for obvious differences in erosion or crater depth.

A Monte Carlo simulation was designed to create randomly-distributed impact points within the initial study region. The separations between all unique pairs of random impacts are computed as great-circle distances. These are tallied to produce a distribution we would expect if impactors were single bodies, and their impact locations are due solely to chance.

Table 1: Candidates for Doublet Craters in Study Area

Crater Pair	*Longitude*	*Latitude*	*Diameter (km)*	*Separation (km)*	*Doublet?*
Pair 1	228.633	-9.703	3.2	2.16	Very Likely
	228.367	-9.695	3.5		
Pair 2	216.578	9.367	4.3	1.58	Very Likely
	216.570	9.176	3.7		
Pair 3	252.679	-13.583	3.0	2.92	Likely
	252.938	-13.831	3.2		
Pair 4	251.772	-21.941	3.0	3.26	Likely
	252.024	-22.236	5.3		
Pair 5	218.295	-21.601	3	3.55	Possible
	218.064	-21.974	3.5		
Pair 6	170.487	9.613	10.8	10.47	Very Likely
	171.366	10.54	13.8		

Results: 1084 craters ≥ 3 km were counted in our final study region. 2030 pairings separated by < 20 km are considered potential doublets.

Visual evaluation. We are visually inspecting all potential doublets, evaluating them using our scoring system. Having evaluated 1190 pairs to date, we identified 6 crater pairs that are likely doublets (see Table 1 and Figures 1a through 1f).

Monte Carlo simulation. We generated 1084 random latitude/longitude pairs within the sample region to represent impact locations (the same number of craters observed), and tallied impact pairs into logarithmic bins based on their separation distance, up to 20 km. Results of 1000 runs of the simulation were averaged. These values are graphed as the curve labeled “Random” in Figure 2, along with the separations of observed crater pairs on Ceres tallied into the same bins (“Observed”). Statistically significant excesses in observed crater pairs are seen for all separations from in the bin centered at 2.88km to the maximum separation considered. We suspect that secondary craters, which cluster spatially in non-random patterns, are the cause. Such clusters would produce a larger number of crater

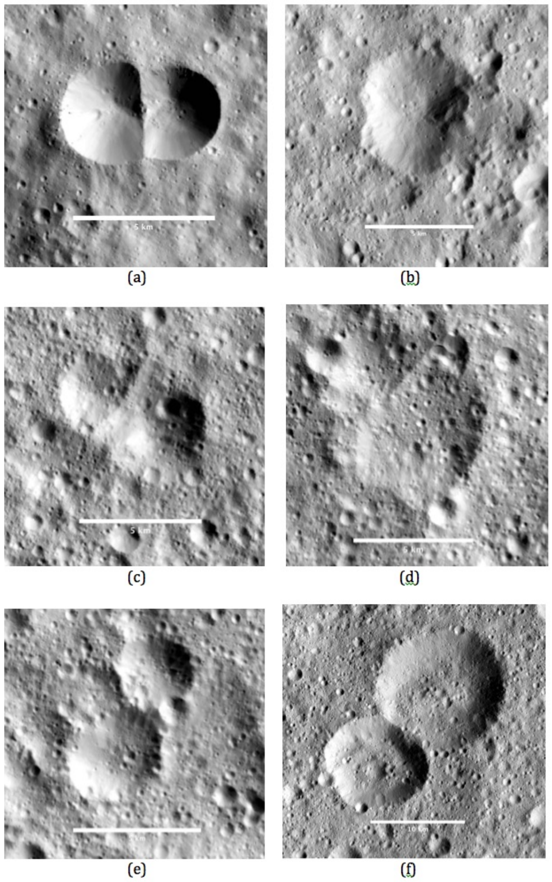

Figure 1: Potential doublet craters: a) “Pair 1” from Dawn FC0048556; b) “Pair 2” from FC00557993; c) “Pair 3” from FC0052195; d) “Pair 4” from FC0051873; e) “Pair 5” from FC0056991; f) “Pair 6” from FC0053565 [15].

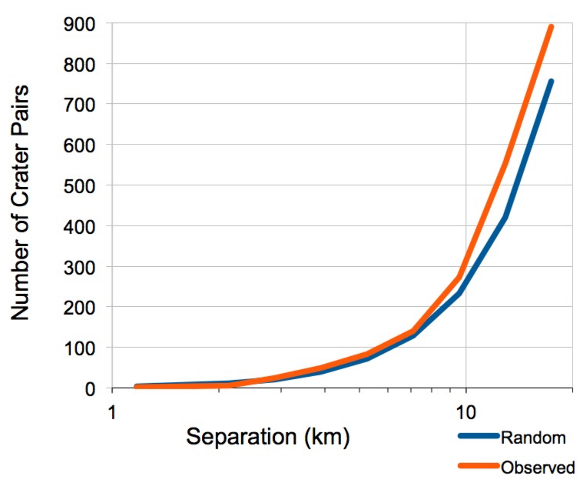

Figure 2: Observed counts of crater pairs by separation, plotted against expected distribution from random impacts.

pairings under our 20km threshold than a random distribution would predict.

Preliminary Conclusion: If Pairs 1 through 6 are true doublets, our work so far places a lower bound on the percentage of doublet craters in this region of Ceres at 0.6% (6 out of 1078 impact events), well below the current estimate of 2-3% for both Earth and Mars [2].

Continuing Work: Secondary craters would increase possible crater pairs, as noted in our examination of the Monte Carlo results. Secondaries also often form pairs [20], mimicking primary doublet impacts. We are currently working to apply morphologically-based techniques that would examine

- Crater rim shape regularity
- Crater depth/diameter ratio
- Asymmetric crater excavation

to help us remove crater pairs from consideration that contains secondaries, or that are coincidental. We will complete our analysis of the remaining candidate pairs prior to the 49th LPSC and report our findings at that time.

References: [1] Oberbeck V. R. and Aoyagi M. (1972) *JGR, 77*(14), 2419-2432. [2] Miljković, K. et al. (2013) *Earth Planet Sc Lett, 363*, 121-132. [3] Oberbeck V. R. (1973) *The Moon, 6*(1-2), 83-92. [4] Oberbeck V. et al. (1977) *JGR, 82*(11), 1681-1698. [5] Trego K. D. (1989) *Earth Moon Planets, 46*(3), 201-205. [6] Trask N. J. et al. (1975) *JGR, 80*(17), 2461-2477. [7] Cook C. M. et al. (2003) *Icarus, 165*(1), 90-100. [8] Melosh H. et al. (1996) *LPS XXVII,* Abstract #1432. [9] Passey Q. R. and Melosh H. J. (1980). *Icarus*, *42*(2), 211-233. [10] Sekiguchi N. (1970) *The Moon, 1*(4), 429-439. [11] Melosh H. J. and Stansberry J. A. (1991) *Icarus, 94*(1), 171-179. [12] Bottke Jr W. F. and Melosh H. J. (1996) *Icarus, 124*(2), 372-391 [13] Johnston W. R. (2016) *Binary minor planets V9.0.* [14] Russell, C. T. and Raymond, C. A. (2011) *Space Sci Rev, 163*(1-4), 3-23. [15] Nathues A. (2016) *Dawn FC2 Calibrated Images V1.0*. [16] H. Hiesinger et al. (2016) *Science,* 353, aaf4759. [17] Christensen P. R. et al. (2009) *Eos Trans. AGU, 90(52)*, Fall Meet. Suppl., Abstract #IN22A-06. [18] Pravec P. et al. (2006) Icarus, 181(1), 63-93. [19] Wren P. F. and Fevig R. A. (2017) *LPS XXXXVIII*. Abstract #2407. [20] Melosh H. J. (1989) *Impact Cratering*, 101.