FORMING 67P/C-G AND OTHER JUPITER-FAMILY CONTACT BINARIES BY TIDAL DISRUPTION?

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Introduction: The irregular and diverse shapes and rotation states of cometary nuclei, including the prevalence of bilobate shapes [1], place important constraints on their origin and evolution. But in any proposed scenario the physical mechanisms are poorly understood. Quiescent agglomeration [1, 2] might lead to lumpy spheroids or layered piles [3]. Original cometesimals might have coalesced [4] as proposed [5] based on the slopes of the layered surfaces mapped on bilobate comet 67P/C-G. An aggressive dynamical history would cause disruptive collisions [6], although the final outcome would include relatively gentle reaccretion of disruption debris, making primeval vs. disruptive origin difficult to distinguish [4, 7]. Sublimation torques would cause elongation and rotational splitting [8], further influencing shape evolution. Another cause of comet nucleus disruption and deformation is planetary tides, as happened to comet Shoemaker-Levy 9 in 1992 [9, 10]. Until detailed 3D radar imaging of internal structure is applied to reveal the formation processes directly [11], we must consider the requirements and probabilities of these scenarios and make inferences from external observations.

Tidal disruption: We evaluate the feasibility of forming a C-G-like contact binary by tidal disruption. First we look at outcomes of tidal disruption to see if morphologically they are likely to explain the bi-lobate structure of 67P. A tidal encounter is a contest between the differential gravity of Jupiter and the rotational acceleration of the nucleus, versus the strength, self-gravity and friction holding it together. According to [8] strength is inconsistent with the formation of S-L/9-like disruption chains. The relevant first-order parameters defining the problem are then: mass of the primary (known), size and mean density of the progenitor comet (guessed; scalable), material properties, i.e. friction and restitution coefficients (guessed), encounter eccentricity (assumed ~1), orbital periapsis q (unknown) and pre-encounter progenitor spin period P (unknown).

We focus on the major unknowns q and P, assuming a prograde rotation with a spin axis normal to the orbit plane. We model a tidal encounter using the discrete element code of [9] to handle the rigid body dynamics, including collisions and resting contacts, and we implement pair-wise gravity between rubble elements. The simulations are carried out in a reference frame centered on the nucleus. The orbit of the progenitor's center of mass is precomputed and the time varying gravity field of the primary is applied to each rubble element simultaneously. The progenitor is generated by allowing a set of 10^4 randomly shaped (but roughly equal-sized) polyehrdal elements to collapse from a loose cloud to a stable resting configuration with $\sim$50% void fraction, with densities scaled to match the bulk density of C-G [1], 0.53 g/cm^3.

For a given value of P we simulate tidal encounters with increasing values of q. An encounter orbit is simulated starting at a distance of about 4 Roche radii from the primary pre-periapsis, and ending at a similar distance post periapsis, by which time the outcome of the encounter, i.e. the number and size of stable clumps, is easily evident. In general, for a given spin period the number of stable clumps post encounter decreases with increasing q. We vary q in small increments to find the range of periapsis values that lead to two roughly equal mass clumps each about half the total mass of the progenitor. Typically at the end of the simulation the clumps are still separating with low relative velocity, the premise being that they will continue on an unstable orbit and experience a low-velocity reaccretion impact in short time. As shown in [4] this type of impact can lead to the desired bilobate shape. Consequently, we find for each of several values of P a small range of periapsis values dq that leads to the progenitor splitting in half. Closer approaches quickly lead to more violent disruptions of the progenitor while farther orbits lead to significant elongation of the progenitor but not sufficient to produce a bilobate shape.

We note however that a splitting in half of the progenitor is only one way of producing binary pairs. In principle it may also be possible that a chain of numerous fragments produced by a more thorough disruption event will nonetheless contain bound fragment pairs. (In this case the progenitor would of course be much more massive than present-day 67/P.) This possibility is much harder to constrain. Not only because it requires we track the fragments through many orbits subsequent to disruption but also because the range of relevant encounter parameters cannot be easily bracketed.

Results: In Table 1 we give the number of gravitationally bound clumps remaining at the end of a tidal encounter N_c with given values of P and q. The range of q values that brackets encounters with $N_c = 2$ is the

Table 1: Number of major clumps remaining following a simulated close approach of a rubble pile comet 67/P with Jupiter. The number of clumps was counted (by eye) when the center of mass of the system passed ~ 4 Roche radii post-periapse (Roche radius based on progenotor's pre-encounter density). Typically clumps are roughly similar sized and remaining debris in the form of small aggregates of few to tens of rubble elements is ignored.

P (hours)	q (R_J)	N_c [a]
8	2	6
8	2.1	3
8	2.11	2
8	2.12	1
8	2.15	1
8	2.2	1
10	1.7	14
10	1.9	5
10	1.95	3
10	1.96	2
10	1.98	1
10	2	1
12	1.7	16
12	1.8	14
12	1.85	6
12	1.88	2.1
12	1.9	1
∞	1.45	10
∞	1.5	10
∞	1.55	3.5
∞	1.6	2
∞	1.65	1
∞	1.7	1

a) Fractional number signifies remaining debris in smaller clumps. For example $N_c = 3.5$ means 3 roughly equal sized clumps and remaining ejecta amounting to about half the mass of each of the clumps.

required range for the purpose of calculating the encounter probability. Although $dq = dq(q, P)$ in principle, in practice is seems that $dq \approx 0.01R_J$, R_J is Jupiter's radius, independent of q or P. We caution that this result might not hold for elongated and/or retrograde progenitors, not considered here [4].

Because of its close approach to Jupiter in 1959, the past orbital history of 67P can only be studied in a statistical sense to understand whether it might have been tidally disrupted in the past. We first investigate the probability of close Jupiter encounters, by generating 30,000 clones from the uncertainty region of the orbit of 67P, propagating each backwards to year -8000 to obtain the probability of Jupiter encounter within a given distance. The close encounters are chaotic so we can extrapolate to longer time: there is a 70% probability of 67P leaving the Solar System in the past 1 Ma, and a 20% probability of 67P impacting Jupiter, indicating Jupiter encounters began << 10 Ma ago. For tidal encounters inside the Roche limit, we find that the probability is ~5±2% per 0.1 R_J, over the past 1 Ma.

As the perijove range required for tidal splitting is an order of magnitude smaller, we conclude that tidal disruption is a feasible but ineffective mechanism of generating contact binaries. However, as explained above, what we have calculated to date is probability of splitting a progenitor in half, which is not the same as the overall probability of generating bound fragment pairs. This latter probability is harder to estimate but it would have to be much greater in order to make tidal disruption an effective binary producer.

For the simulations done here, we find that "binarity" (a bound doublet that will presumably later coalesce) is not all that common, certainly not common enough to explain the prevalence of bilobate cometary nuclei [1]. Here we have attempted to find solutions that give C-G like mass ratios. While a more formal solution would multiply together the probability space of tidal disruption outcomes for binarity, with the probability distribution $P(dq)$ for the chaotic close encounters, it seems that better mechanisms exist to explain 67P/C-G.

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