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Modeling the Breakup of Comet Shoemaker-Levy 9

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Abstract. We present preliminary simulations of the tidal breakup of Comet Shoemaker-Levy 9. The simulations investigate the manner in which bulk density, diameter, spin period, and orientation of the spin axis affect the breakup of the comet. The diagnostics used to explore these parameters are the position angle, length, and mass distribution of the fragment train. The simulation results are compared to a large and detailed observational record of the comet's encounter, including HST observations. The analysis could not have been accomplished without data provided by space-based instrumentation. Solar system studies like these that require high spatial resolution will benefit from NGST.

1. Introduction

In 1992 Comet Shoemaker-Levy 9 (SL9) passed within 1.3 jovian radii of Jupiter and was pulled apart into a fragment train that coalesced into ~ 21 cometary clumps. These clumps, discovered by Shoemaker et al. (1993), were later observed with HST (Weaver et al. 1994, 1995) and were tracked until they impacted Jupiter over a span of one week in 1994 (Chodas & Yeomans 1996).

The SL9 breakup required a very fragile progenitor, possibly a "rubble pile" (Asphaug & Benz 1994; Richardson et al. 2002). Observations of the SL9 clumps—their number and relative size—and of the fragment train as a whole—its length and position angle on the sky—constrain the properties of the progenitor. Previous studies (Scotti & Melosh 1993; Boss 1994; Solem 1994; Asphaug & Benz 1994, 1996; Rettig, Sobczak & Hahn 1996) constrained the progenitor bulk density to be between 0.5 and 1.0 g cm^{-3} and the diameter to be between 1.5 and 2 km. The progenitor spin is degenerate with bulk density, since both determine the effective surface gravity, but reasonable values of the bulk density imply spin periods no faster than 6 h with obliquity less than 90° (Asphaug & Benz 1996).

Observations of the dynamics of the SL9 clumps also provide clues as to the nature of the progenitor. Evidence for secondary fragmentation was observed (e.g. Fragment Q1 was inferred to have separated from Fragment Q2 in April 1993; see Sekanina 1996), which is a strong test for the rubble pile hypothesis. From the HST observations, the dust production and sizes as well as the outflow

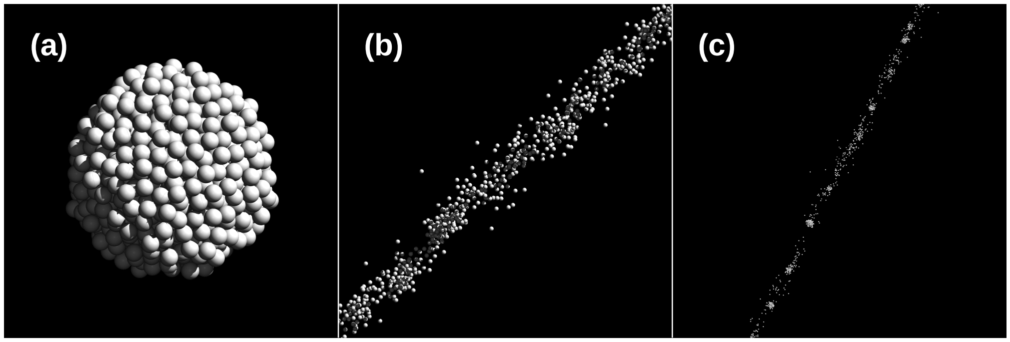

Figure 1. Snapshots of the tidal disruption of a rubble-pile comet. Clumps form via gravitational instability along the fragment train.

velocities suggested the dust was collisionally produced and the fragments were at least partially in the form of "swarms" of particles (Rettig et al. 1996; Hahn, Rettig & Mumma 1996; Hahn & Rettig 2000). There was a mostly verbal debate as to whether the fragments were solid objects or swarms of particles. The answer is critical to understanding the nature of cometary nuclei.

2. Simulations

Adopting the rubble pile scenario that the SL9 progenitor consisted of tiny fragments held together by gravity, we seek to more precisely constrain the SL9 progenitor properties using a sophisticated numerical code called `pkdgrav` (Richardson et al. 2000) that can handle both particle collisions and gravitation. In this scenario, jovian tides stretch the fragments into a linear assemblage that collapses into distinct clumps under its own self gravity once outside the Roche zone of the planet (Fig. 1).

To date we have tested over 100 configurations varying progenitor bulk density (0.3, 0.5, and 0.7 g cm^{-3}), diameter (0.8, 1.0, and 1.2 km), spin (6, 9, 12 h, and no rotation), and obliquity (spin vector pointing along the orbital momentum vector, pointing directly toward Jupiter, pointing along the direction of motion, and one case in between these three). The initial conditions for each run were based on a numerical integration of Fragment K from 1994 July 6.0 to a point before perijove when the comet was outside the Roche limit at 6 jovian radii. The integrations included Saturn and the Earth, spanned over 720 days of real time, and were performed using $\sim$1000 particles each.

For each run the position angle and length of the fragment train was measured as a function of time. These were measured as they would have been observed from Earth, so as to compare with observation. Uniformity of the fragment train was measured simply by comparing the relative masses of each clump at a given instant. Identification of clumps was performed using an automated procedure that ignores groupings of fewer than 3 particles.

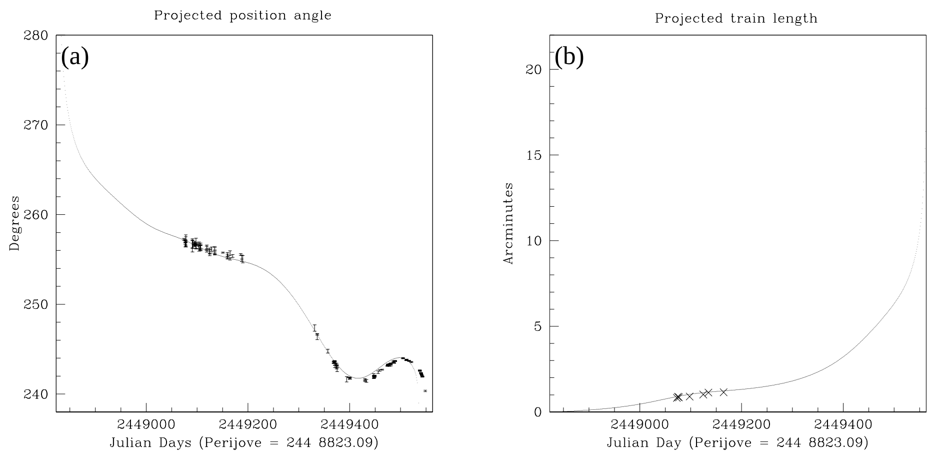

Figure 2. Position angle (a) and train length (b) as seen from Earth. Crosses or points with errorbars are actual observations.

3. Results

The position angles for all the simulations showed good qualitative agreement with the observations, apart from systematic deviations at late times which we ascribe to errors in the initial conditions (which did not include observations taken just before impact). However, the simulations did show significant mutual differences at early to mid times, with separations up to 3–5°, which rules out some cases based on observations, e.g. runs with high density ($0.7\ \mathrm{g\ cm^{-3}}$) and no spin, and runs with low density ($0.3\ \mathrm{g\ cm^{-3}}$) and fast spin (6 h). An example of a reasonable fit is shown in Fig. 2(a).

Measurements of the observed train length were published only over a short interval, between March and April 1993 (Scotti & Melosh 1993), and are dependent on instrument sensitivity. The measurements serve as a lower limit: if the simulated train is shorter than the observed length, then that case can be ruled out. Conversely, a simulated train may be much longer than that of the observations if some fragments were too faint to observe. So far in our simulations no set of parameters can be eliminated on this basis alone (see Fig. 2(b) for an example). We also measured a near constant rate of growth of the fragment train, suggesting that the rate at which the fragment train grows is almost entirely independent of density, diameter, rotation rate, or rotation direction.

Constraints provided by published observations of fragment sizes based on relative intensities (Weaver et al. 1995) are in agreement with the position angle results, i.e. that high density/low spin and low density/high spin cases can be ruled out. This gives us confidence that we have bracketed the relevant regime so that we can focus on a narrower set of parameters for determining the overall best fits to the data in future work. We also note that during our simulations some variability in clump mass was detected, suggesting each individual fragment was actually a swarm of particles that was constantly changing. To explore this in more detail a series of very high resolution simulations will provide more resolution in particle size to invesigate cases of secondary fragmentation.

4. Future Work

The current work has provided insight into constraints on tidal disruption outcome, e.g. how rotation affects the position angle of the fragment train. Within any given subset of parameters the density was a dominant factor in determining the quality of fits to observations. Though the observational bias involved with train length prohibits the combination of all the constraints to determine a single set of best-fit parameters at this time, the elimination of some provides insight into the range of possible parameters as a whole. The mass fraction analysis ruled out most of the high density/slow spin and low density/fast spin cases, and the position angle measurements supported this finding.

Much of the data set was the result of space-based observations that provided the spatial resolution required to analyze the dust comae and secondary fragmentation events. It is only with such capabilities that a better understanding of the formation and destruction of cometary nuclei can be produced. Future observations, with new-technology space-based telescopes, will provide the community with many innovative ideas and directions not conceived of previously.

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