Rotational Disruption of Cometary Nuclei

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with the aid of Derek Richardson, Bill Bottke, and Stephen Lowry
(somebody ought to update this)

• Dynamically new comets 10%
• Returning long-period comets 4%
• Short-period comets 1%

• Splitting rate appears to be correlated with dynamical age
• No correlation observed with perihelion distance, time before or after perihelion, inclination, etc.
• Best dynamical model of long-period comets from the Oort cloud (Weissman 1979) included 15% of LP comets that never split
Why Do Comets Split?

- **Tidal disruption**: fairly obvious – passage through Roche limit: Shoemaker-Levy 9, Kreutz sun-grazer family
- **Random disruption**: unknown
- Most common event is comet shedding of one or more fragments at velocities of a few meters/second
- HST imaging shows many more smaller fragments may be involved
- **Suggested mechanisms**
  - impacts (e.g., Harwit, 1968) – probability too low
  - volatile gas pockets (e.g., Whipple, 1963)
    - unlikely in low density, porous nucleus
  - rotational spin-up due to torques from asymmetrical outgassing (e.g., Davidsson, 1999, 2001)
Comet Shoemaker-Levy 9: Tidal Disruption

• Chain of 21 comets discovered in eccentric orbit around Jupiter in March, 1993
• 1992 perijove passage at $1.6 \ R_J$ – tidally disrupted comet
• Fragments impacted Jupiter in July, 1994
• Probably captured into orbit ~ 1929. Previous orbit was probably a Centaur object, similar to 29P/SW-1
Comet 73P/SW-3 Fragment B: Random Disruption

- SW3 – random disruption event: Comet split into several fragments in 1995. (Also split soon after discovery in 1930)
- Close approach to Earth in 2006 allowed observations of major disruption events while inbound to perihelion
Comet LINEAR
Fragments
August 5, 2000
(D/1999 S4)

University of Hawaii

Hubble Space Telescope
WFPC2

NASA and H. Weaver (JHU)
STScI-PRC00-27
Pravec et al. (2003), In Asteroids III
Modeling of Comet Rotational Spin-up


• For reasonable values of nucleus size, shape, and activity level, change in period can be 0.1–2 hours per perihelion passage

• Change in pole direction can be ~2–20 degrees per perihelion passage

• Pole will random walk, resulting in different changes on each perihelion passage

• Explains observed variations in behavior of non-grav forces for many short-period comets; Also, lack of non-grav forces role in dynamical evolution of long-period comets.
N-Body Simulation of Rubble Pile Nucleus

- 209 particles, each 170 m in radius
- Nucleus is gravitational aggregate – no binding forces
- Nucleus prolate ellipsoid: $4 \times 2 \times 2$ km; $M = 4.7 \times 10^{15}$ g
- Initial bulk density: 0.6 g cm$^{-3}$; porosity $\approx 48\%$
- Initial spin period: 8 hours
- Two active areas: orange and purple particles, one on each end; active only in sunlight, thermal lag (sun at top, $+Y$)
- Modeled with PKGRAV program (Richardson et al. 2000)
- Particles “bounce” when they hit, with modest frictional dissipation force both vertically and horizontally
Axis and Spin Stats for Largest Rubble Pile

- Axis Lengths $a_1, a_2, a_3$ (km)
- Axis Ratios $q_a, q_e$

Spin Components $a_1, a_2, a_3$ (km/h)
Spin Magnitude $\omega$ (km/h)

- Time $t$ (JD): 0, 2, 4, 6
- Values: 6.5 hours, 7 hours, 8 hours
Predictions of a Rotational Spin-Up Model

• Split comets should be relatively fast rotators
  – C/1999 S4 LINEAR:  5.2 hr (Lisse et al. 2006)
  – C/Hyakutake:  6.27 hours (Schleicher & Osip 2002)

• Split comets should preferentially be small
  – Only 3 split comets with measured radii:
    69P/Taylor:  $r = 3.6$ km; 79P/duToit-Hartley:  $r = 1.4$ km
    C/Hyakutake:  $r = 2.4$ km — typical values

• Split comets may have relatively high nongravitational forces
  – 9 split JFC comets:  mean $A_1 = 0.571$, $A_2 = 0.179$
  – 50 JFC comets:  mean $A_1 = 0.385$, $A_2 = 0.049$
Conclusions

• Rotational spin-up provides a viable mechanism for explaining random disruption of cometary nuclei

• Disruption events occur randomly as nucleus period crosses some rotational threshold, depending on shape, density, binding strength, activity, asymmetry, etc.

• Ejection velocities ~ meters/sec

• Explains repeated disruption events from some nuclei

• Events can be totally disruptive

• Also explains why some nuclei appear to be rotationally de-spun: e.g., Halley, Tempel 1
Analytic Model

• Already done by many researchers: Gutierrez et al. (2003), Nieshtadt et al. (2003), Keller et al. (2000), etc.

• General result is that nucleus rotation period can change by hours in 1-10 returns

\[ P_o = 8, 10, 12 \text{ hr} \]

Rotating, ellipsoid nucleus
Typical JFC solar orbit
Water ice sublimation only
Why Do Fragments Look as Bright as the Primary?

For nucleus that is mostly covered by an inactive crust, the splitting event exposes equal areas of fresh ices on both the primary and the secondary (after Whipple).
57P du Toit-Neujmin-Delporte, 2002

18 fragments observed, 30 arc-minute chain