That’s the Way the Comet Crumbles:  
Splitting Jupiter-Family Comets  

Yanga R. Fernández∗

University of Central Florida, Department of Physics, 4000 Central Florida Blvd.,  
Orlando, FL 32816-2385 U.S.A.

Abstract

Our current understanding of split, Jupiter-family comets is reviewed. The focus  
is on what recent studies of comets have told us about the nature of the splitting  
phenomenon. The goal is to not repeat the information given in recent reviews of  
split comets, but to build upon it. In particular, we discuss comets that have suffered  
splitting or fragmentation events in the past few years. These include comets (a)  
57P/du Toit-Neujmin-Delporte, observed with a long train of fragments in 2002; (b)  
73P/Schwassmann-Wachmann 3, which split in 1995 and was extensively studied  
during its relatively close passage to Earth in 2006, during which dozens of fragments  
were discovered and studied; and (c) 174P/Echeclus, a Centaur and potentially  
future JFC, which split in late 2005 and was the first such Centaur observed to do  
so. We also discuss recent observations by SOHO of split comets that are likely of  
short-period. The Spitzer Space Telescope has observed many JFCs and provided us  
with unprecedented detailed views of cometary debris trails, which may be thought  
of as a middle ground between “normal” ejection of micron-sized dust grains and  
the cleaving off of meter-to-kilometer sized fragments. We will also discuss potential  
breakthroughs in studying splitting JFCs that may come from future surveys.

Key words:  
comets – splitting, comets – individual (57P, 73P, 174P), comets – evolution  
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∗ Corresponding author. Tel.: +1 407 8236939; fax: +1 407 8235112.  
Email address: yan@physics.ucf.edu (Yanga R. Fernández).
1 Introduction

The “typical” Jupiter-family comet (JFC) loses mass through a relatively slow process of volatile sublimation and dust entrainment. Common mass loss rates when a JFC is near perihelion are roughly $\sim 10^{1-3} \text{ kg/s}$ (A’Hearn et al., 1995), depending on the size of the nucleus’s “active area.” This indicates that nominally the cometary nucleus could disintegrate away probably only after thousands of orbits around the Sun. This end-state of a JFC has never been directly observed, although such very tiny comets (meters in diameter) that are about to disintegrate would be difficult to discover. In any case current thinking (e.g. Meech and Svoren, 2004) holds that most JFCs end their lives either by plunging into the Sun, colliding with a planet, simply turning off and becoming asteroid-like, or by catastrophic fragmentation.

This review will focus on this last option and its attendant large mass loss rate. The primary motivation for studying split comets is that they are laboratories for understanding cometary structure and bulk mechanical properties. Since this can give us clues about how comets are put together, split comets can be an important window for investigating the details of planetary formation and specifically the accretion of solids into icy planetesimals. As mentioned above, split comets also represent an aspect of cometary evolution. Since split comets expose previously buried material to the space environment and thus to our telescopes, they give us a way to probe chemical and thermophysical changes in cometary nuclei.

In this paper, recent developments in our understanding of split comets will be discussed. An excellent recent review of this topic is provided by Boehnhardt (2004), and there have been several likewise good reviews before that (e.g. Sekanina, 1982, Hughes and McBride, 1992, Sekanina, 1997, Boehnhardt, 2002). The goal of this paper is to not duplicate that earlier work but rather to provide updates on work occurring in the interim.

2 Observational Aspects of Splitting

Conceptually, the question of “how do you know when a comet has split?” is easy to answer. The observational manifestation of a splitting is a condensation that appears away from the head of the comet but moving with very nearly the same proper motion. However not all near-nuclear condensations are actually indicative of a split; the condensation may or may not hold a solid body and may be simply (e.g.) a trick of perspective on jet features in the coma, or a clump of dust from an outburst. The overall dust production rate and the complexity of coma morphology can make the actual identification of a real
splitting problematic. In particular, a splitting is often associated with an outburst or a brightening, potentially making it even more difficult to identify a fragment.

Interestingly, a fragment may not appear even when a comet brightens dramatically. For example, comet 29P/Schwassmann-Wachmann 1 has frequent outbursts (see, e.g., Jewitt, 1990), yet no fragment has ever been seen.

On the other hand, a comet that appears perfectly “typical” could have had a recent splitting, but the fragments may be more than a few arcminutes from the head, i.e. beyond the field-of-view of a typical CCD camera. Due to sporadic monitoring of most comets, a fragment will not always be seen in the near-nuclear region; it may not be discovered until well after the split, as was the case for fragment B of 57P/du Toit-Neujmin-Delporte (Marsden, 2002a), which was found 0.2° away from fragment A, the comet’s main head. The even more extreme case is the paternity of comets 42P/Neujmin 3 (discovered in 1929) and 53P/van Biesbroeck (discovered in 1954), which were found (Carusi et al., 1985) to be pieces of one comet that split after a close approach to Jupiter in 1850.

Another problem in determining whether a split has happened is simply faintness. A 50-meter radius bare nucleus that is 2.0 AU from the Sun and 1.0 AU from Earth – all reasonable numbers for a cometary fragment – will have an R-band magnitude of about 25 (for a geometric albedo of 0.04), which is beyond the reach of many facilities. Even when such a fragment is actively outgassing and thus brighter, the observation itself may not be done in such a way as to detect the fragment.

All this makes determining the frequency of fragmentation among JFCs relatively difficult to measure. A list of published instances of JFC fragmentation is given in Table 1, but since many comets have long intervals (months or years) where no observations are obtained by either professionals or amateurs, this is naturally a lower limit of the true roster. Hughes and McBride (1992) estimated that a JFC has 0.3% chance of splitting per perihelion passage, based on the historical record of observed fragmentations. Chen and Jewitt (1994) observed a sample of 34 JFCs with CCDs in the late 1980s and early 1990s, and found 2 had split, corresponding to a ~1% chance of a JFC splitting per year. If these are accurate estimates of the splitting rate, one remarkable consequence is that over the course of the ~ 10^3 orbits that a typical JFC will be active (Levison and Duncan, 1997), it can expect to split perhaps dozens to hundreds of times. As noted by Chen and Jewitt (1994), while JFC splittings may be perceived as being rarer than splittings by near-isotropic comets, a given JFC will shed fragments many times during its active life.

This finding suggests that the shape and rotation state of a JFC is intimately
tied to the specific fragmentation events it has suffered, since the amount of mass coming off in a fragment can be significant compared to the total mass lost by normal outgassing in the course of an orbit. Suppose a JFC with perihelion at 1 AU and aphelion at 5.2 AU (Jupiter’s distance) has a mass loss that is 200 kg/s at perihelion and is proportional to the inverse-square of heliocentric distance. This comet will lose about $4 \times 10^9$ kg in one orbit. If the effective radius of the nucleus is 2 km, and the density is about 400 kg/m$^3$, that is just 0.03% of the comet’s total mass. If the comet is “active” over 10% of its surface, the mass loss from those active areas erodes about 2 m deep. If an equivalent mass were to come off as a spherical fragment, however, the fragment would be 130 m in radius. This is a reasonable size for a “typical” fragment of a JFC (Boehnhardt, 2004). Such a splitting would represent a significant change in gravitational field, angular momentum, and topography.

As mentioned earlier, we have not discovered a population of very tiny comets. We do not have observational evidence of a population of deka- or hectometer sized JFCs that could be made up of fragments. The discovery biases almost certainly play a role in this, although, as Meech et al. (2004) showed, if one accounts for the biases it seems that the JFC size distribution really does fall off below ~1 km. In other words if the JFC size distribution were a power-law, we should have discovered more comets smaller than 1 km than we actually have. This suggests that most deka- or hectometer sized JFC fragments will not stay as coherent bodies for long (years to decades) but eventually disintegrate.

In any case, directed, deep searches for smaller JFCs would be useful so that we could directly address this problem with as little observational bias as possible. In particular, a search that covers the projected orbits of several JFCs would put constraints on the lifetimes of the fragments. For example, in Fig. 1 we show a Spitzer Space Telescope mosaic of the vicinity of comet 73P/Schwassmann-Wachmann 3 in May 2006. Approximately three dozen fragments can be seen; how many will survive to the comet’s next perihelion in 2011? (We discuss this comet further in §4.2.)

### 3 Causes of Splitting

While tidal disruption as a mechanism for splitting comets is well understood, it is responsible for only a small fraction of observed splits. Briefly, a comet passing close enough to a planet (usually Jupiter) or the Sun will feel different gravitational forces on one end of its nucleus compared to the other. The difference in forces can be strong enough to overcome the body’s cohesion. The extremely low tensile strength and high porosity of cometary nuclei, as suggested most recently by the Deep Impact visit to comet 9P/Tempel 1 (Ernst and Schultz, 2007; Holsapple and Housen, 2007; A’Hearn, 2008), in-
dicate that a tidal force need not be that strong to successfully rip a comet apart. However, in only one case – comet D/1993 F2 (Shoemaker-Levy 9) – are we very sure that tidal disruption is the cause of the fragmentation. Comet 16P/Brooks 2 probably also suffered this fate but it was not discovered until a few years after the purported close-approach.

For all the other comets in Table 1, tidal disruption could not have been the cause of the split. In these cases, we are no closer to understanding why a particular comet splits when it does than we were when [Boehnhardt (2004)] wrote his review. He gives four other methods that could cause splitting: by fast rotation, by thermal stress, by internal gas pressure, and by impacts. Since that review was written, our understanding of the thermal properties of cometary nuclei has improved as a result of the Deep Impact experiment. For example there is stronger evidence now that the thermal conductivity of cometary nuclei is extremely low ([Sunshine et al., 2007; Groussin et al., 2007]), so low that the thermal pulse can penetrate only a few centimeters due to diurnal heating. This means that on diurnal time scales thermal energy may not be transported effectively into the comet’s interior any faster than the surface can itself be excavated by normal cometary activity. The existence of abundant CO$_2$ – with its low sublimation temperature – in P/Tempel 1’s coma ([Feaga et al., 2007]) also indicates that the comet could not have been entirely baked out. Of course these are results for just one comet, but if they are indicative of the “average” thermal properties of a JFC, then perhaps it may be less likely for JFCs to split as a result of thermal stress. On the other hand, the low strength of a JFC means that one can conceive of localized structures (e.g. sheer cliffs in depressions or concentrations of less porous rock) where thermal stress in just a small volume could cause a much bigger volume to break off. This relates to more fundamental questions of nucleus structure about which we do not yet have much data. How well are the volatiles and refractories mixed within the nucleus? Is the high porosity manifest in micrometer or macro-scales? How common is significant topography?

4 Recent Results

4.1 Comet 57P/du Toit-Neujmin-Delpporte

Fragment B was discovered in July 2002 well away from the main part of the comet. Soon after, we ([Fernandez et al., 2002]) discovered eighteen more fragments (named “C” through “T”) along the line of variation (the projected orbital path) and extending out 27 arcminutes from the comet’s head. A montage of these individual fragments as seen on UT July 17 is shown in Fig. 2, along with a plot of the fragments’ positions. The fragments had varying
brightnesses ranging from 20 to 23.5 mag in R-band. They also had widely varying degrees of condensation; some fragments were nothing more than blobs of dust with no central source, such as I and P. All fragments seemed to be actively outgassing, though with apparently varying production rates.

Interestingly, there was no outburst in 2002 associated with this shedding of mass. There was a significant outburst at the previous apparition, in 1996, when the comet was observed to be about 5 mag brighter than expected. However dynamical analysis of the largest fragments by Sekanina and Chodas (2002) suggests that they could not have broken off six years earlier.

The fragments must represent a significant fraction of the comet’s total mass. How much mass, and what fraction is it? The size of the nucleus before fragmentation is unknown, but Lowry and Fitzsimmons (2001) derived an upper limit to the radius of 1.1 km. So for an assumed density of 400 kg/m$^3$, the upper limit to total mass would be approximately $\sim 2 \times 10^{12}$ kg. The activity of the fragments makes their size estimation problematic, so a mass estimate is even more difficult. However we can make an order-of-magnitude analysis. For example, fragment G had an R-band magnitude of about 22.5, which at the distance of 57P at the time, would correspond to a solid body with effective radius of about 130 meters. Such a body alone would be $\sim 0.1\%$ of 57P’s total mass. This is an overestimate for this particular fragment since cometary dust contributes to the magnitude, but there are a few fragments that are likely much bigger than G, so this is a reasonable order-of-magnitude estimate of 57P’s mass loss.

A slightly more sophisticated analysis would be to naively convert all 19 fragment magnitudes to sizes, and thus create a cumulative size distribution (CSD). One finds that such a distribution is fairly shallow, with $N(> R)$, the number of objects with radius bigger than $R$, proportional to only $R^{-1.3}$. While this totally ignores the obvious activity of the fragments, if activity scales roughly with the fragment’s surface area, the power-law slope of the size distribution will be unaffected. This slope means that the total mass $m$ contained in fragments up to some size cutoff $R_0$ is proportional to $R_0^{1.7}$. This suggests that much of the fragmented mass is in the largest pieces such as B, E, and F.

Interestingly, the CSD slope is shallower than that of large dust grains found in JFC trails, as measured by Reach et al. (2007a). They found $N(> R) \propto R^{-2.3}$ for grains over 0.25 mm. Whether this is a clue as to the physical mechanism behind fragmentation remains to be studied.

The real significance of the discovery of the train behind 57P is that it was the first time so many fragments had been observed around a surviving, non-tidally disrupted comet. Other comets have had as many fragments but only while
being completely broken apart or after passage by Jupiter or the Sun (e.g., comet C/1999 S4 (LINEAR), comet D/1993 F2 (Shoemaker-Levy 9), and the Kreutz sungrazers). It motivates the question of whether shedding events happen more frequently than thought and are just being missed due to the extreme faintness of the fragments. Indeed, the sheer length of 57P’s train suggests that there were several fragmentation episodes in the past. If a JFC loses only fragments of magnitude 23, 24, or fainter, only deep imaging of the comet during the course of monitoring will reveal them.

The case of 57P also raises questions about the endurance of the smallest fragments. Sekanina and Chodas (2002) state that fragment F would have left the primary nucleus – i.e. fragment A – about 14 months before the discovery observation; at discovery, F was 6 arcmin from Fragment A. They predicted the future motion of fragment F based on this model, but unfortunately apparently little if any data could be obtained by observers to corroborate or refute the hypothesis. However, if true, it suggests that large fragments farther down the train could have been released at even earlier times. Fragment T is 27 arcminutes from fragment A – 4.5 times farther than fragment F. T could have left the main nucleus (on its own or as part of another fragment) years in the past. This would not necessarily be unprecedented, since as Boehnhardt (2004) notes JFC fragments can have long endurance (hundreds of days), and there is indication that JFCs can split most anywhere along their orbit. The estimation of the endurance of fragment T would also depend on at what relative speed it left the nucleus. In any case, fragment T is a fairly small fragment: could it have survived for years, and are we just now seeing the end of its life? Is it really persistent despite its small size? It is also possible that fragment T is a subfragment of a brighter fragment, say fragment S. Even so, the distance between S and T is appreciable (3.2 arcmin) and suggests an endurance for T of several months despite its small apparent size. Beech and Nikolova (2001) have modeled the survival times of fragments and show that small, clean icy fragments can survive for months after separation, although whether or not fragment T can be clean “enough,” is uncertain. The images in Fig. 2 show cometary dust, not gas, and so there must be some “dirtiness” to the fragments, which would shorten their lives (Hanner et al., 1981; Lien, 1990).

The faintness of the fragments, and then later the fact that the comet was post perihelion and at unfavorable elongation, prevented detailed follow up. The endurance of the fragments was not directly measured. Therefore further observations of the fragments and of the main comet itself at future apparitions would be extremely useful to understand how this comet is evolving.
One of the most-widely observed split comets since D/Shoemaker-Levy 9 has been 73P/Schwassmann-Wachmann 3, which first split in 1995 and approached to within 0.07 AU of Earth in May 2006. This recent visit was a monumentally important apparition scientifically since it would allow us detailed studies of bright and relatively-fresh fragments – fragments whose ices had formerly been deeply embedded within the comet’s nucleus but were now exposed to sunlight. In a way, it was similar to the Deep Impact experiment in that 73P provided us with a close-up view of subsurface pristine cometary material.

A review of this comet’s behavior was given by [Boehnhardt et al. (2002)](#) and by [Sekanina (2007)](#), which we briefly summarize here. This comet split into several fragments in 1995, some of which deactivated or disintegrated before the apparition was over. At the comet’s next apparition in 2000 and 2001, two of the 1995 fragments, B and C (the primary part of the comet), were recovered, and two new fragments, E and F, were confirmed (although apparently E broke off from C during the previous orbit). F disappeared later in the apparition but the stage was thus set for the 2006 apparition: would B and C survive another perihelion passage? Would E have survived? Would there be a train of even more fragments?

The result was that in April and May 2006 over 60 fragments were found – including B and C but not E. The proximity to Earth certainly helped; a fragment of the same size as 57P-G (mentioned in the last subsection) would be about 3 mag brighter at 73P’s geocentric distance. In any case some of the fragments were very short-lived, lasting for only a few days. Amateur astronomers contributed greatly to the census of fragments, in fact even finding fragments that disappeared within a day and so could not be followed up and formally named. Lists of the fragments and relevant info have been compiled by [Sekanina (2007)](#) and [Birtwhistle (2008)](#), and the former also discusses some preliminary work on describing the cascading fragmentation.

One of the many spectacular images from this apparition is shown in Fig. 3, which comes from the Hubble Space Telescope. Fragment B was a dynamic and rapidly changing fragment for much of the apparition, and this image epitomizes this. It shows several subfragments (a.k.a. “mini-comets”) tailward of fragment B itself. These pieces are probably dekameter in scale, and a sequence of images from HST show these fragments moving down the tail, outgassing until they disintegrate away in timescales of only hours or days. The image field-of-view is only about 25 arcseconds. A wider scale picture is shown in Fig. 1, covering almost 5 degrees of sky along the comet’s orbital path. The dynamics of the small fragments in Figs. 1 and 3 have been analyzed by [Reach et al. (2007b)](#), who found that the HST fragments are strongly affected
by the non-gravitational reaction force due to outgassing – suggesting a high volatile content. On the other hand, the “meteoroids” in the Spitzer image are moving as would be expected simply from radiation pressure and solar gravity – suggesting a low volatile content. This perhaps could be explained as an evolutionary effect, where the HST fragments dry out to become the Spitzer fragments. This does require that the HST fragments would have to have sufficient size and sufficiently low rock-to-ice ratio to be able to survive for the several days that they are seen in the HST data. Unfortunately, identifying the fragments seen by HST on April 18 with some part of the extended emission seen in the Spitzer mosaic on May 4 would be problematic since the spatial resolutions are so different and the time gap is so large.

The variability of fragment B is in stark contrast to fragment C, the primary fragment (Sekanina, 2007). That fragment remained relatively stable, with only slowly varying activity, nowhere near the frequency and amplitude of changes seen from night-to-night (and sometimes within a night) in fragment B. The two fragments must be roughly comparable in size, yet the specifics of B’s shape and the location of its volatiles has made apparently a huge difference in the evolution.

Many observations of comet 73P were obtained during its apparition, and analysis on these rich datasets continue. We summarize here some of the exciting results and apologize for oversights.

Arguably some of the most important findings involve the composition. Overall, 73P seems to be depleted in CH$_3$OH, C$_2$H$_6$, and C$_2$H$_2$, but has “typical” abundance of HCN (Villanueva et al., 2006; DiSanti et al., 2007; Kobayashi et al., 2007). This means that this ecliptic comet that came from the trans-neptunian region is compositionally similar to C/1999 S4 (LINEAR), a carbon-chain depleted Oort Cloud comet (DiSanti and Mumma, 2008). Furthermore it is unlike its fellow ecliptic comet 9P/Tempel 1 (DiSanti and Mumma, 2008). This matching of compositions across dynamical classes hints that there was sufficient mixing in the protoplanetary disk to allow individual icy planetesimals to accrete material from various regions. In other words perhaps there is not necessarily a compositional distinction that exactly matches the dynamical distinction of ecliptic comets forming beyond Neptune and Oort Cloud comets forming among the giant planets. Alternately, there could simply be interlopers polluting the dynamical groups. In particular, we are only now starting to build up a statistically significant sample of the parent-molecule composition of JFCs (Mumma, 2008) to build upon the daughter-species work by (e.g.) A’Hearn et al. (1995) and Schleicher and Baint (2008). We can note that 73P is a “depleted” comet in the A’Hearn et al. (1995) taxonomy and 9P is “typical;” as the parent species of more JFCs are observed, 73P and 9P can be placed into better context.
Several people compared the two main fragments, B and C, to each other (e.g. Biver et al., 2006; Villanueva et al., 2006; Schleicher et al., 2006; Dello Russo et al., 2007; Kobayashi et al., 2007). The consensus result is that B and C have similar composition. This is an important finding since both fragments are relatively large fractions of the original comet and so show us fresh material that formerly was very deep inside the nucleus. They should be excellent laboratories for determining heterogeneity – i.e., whether large blocks of the comet have different compositions. No such effect was found, and this is in stark contrast to comet 9P, where the heterogeneity was quite obvious after the Deep Impact flyby (e.g. Feaga et al., 2007). The fact that 73P seems to be both (a) homogeneous and (b) different from what may be currently considered “typical” composition suggests that this comet had an atypical formation history. However this is speculative and, again, we are suffering somewhat from a small JFC sample. In any case we clearly see the vital need for more surveys of JFC composition.

One important additional result regarding composition was presented by Schleicher et al. (2006). They showed that the B and C fragments both have the same “depleted” abundance of CN, C$_2$, and C$_3$ relative to water. As mentioned, since the fragments were outgassing relatively pristine material, this suggests that this depletion seen in many JFCs could not be an evolutionary effect, but rather is primordial. It may be indicative of the chemistry happening in the protoplanetary disk at the location where at least some of the JFCs formed.

The proximity of 73P motivated many observers to investigate the physical properties of the fragments. Of primary concern were the fragments’ sizes and masses. Boehnhardt et al. (1999) observed the comet in 1994, before breakup, and estimated an upper limit of 1.1 km for the radius. Some of the most exciting data on the nuclei after break-up were obtained by Howell et al. (2007), who used radar to obtain Delay-Doppler maps of fragments B and C in May 2006. 73P was at the time only the second comet so imaged. The data show that fragment B is at least 0.2 km in radius and that fragment C is about 0.5 to 1 km in radius. These results are consistent with earlier estimates of those two fragments’ sizes (Boehnhardt, 2002; Toth et al., 2003, 2005, 2006). While fragment C is the primary remnant of the comet, fragment B took a significant fraction of the mass with it.

Knowing the rotational states of the larger fragments could potentially give insight into the fragmentation process, the dekameter-scale structure of the comet, and/or the cometary mass. So far, there have been reports only for fragment C (e.g. Storm et al., 2006; Toth et al., 2006). Fragment B was so active and changing on such short timescales that obtaining either a photometrically- or morphologically-derived period may be challenging. Coma structures were seen however (e.g. Bonev et al., 2008) so a sufficient baseline of observations could prove fruitful. Rotation periods for the other relatively bright fragments,
such as G and H, have not been reported to our knowledge.

Images such as Figs. 1 and 3 make it clear that there is a continuum of sizes among the fragments. An analysis of the size distribution of all fragments has yet to be presented, but Fuse et al. (2007) have studied a group of fragments that at the time had all just recently broken off fragment B. Their processed image is shown in Fig. 4, and was obtained a few weeks after the HST image in Fig. 3. They identify 54 fragments in their data, all of which were active, and measured the luminosity of each. Assuming that the activity is proportional to the fragment surface area, they then derive a CSD power-law slope based on their 54 fragments: \( N(> R) \propto R^{-1.1} \). This is tantalizingly similar to the rough CSD slope for 57P as discussed in §4.1. Both CSD slopes are much shallower than the overall JFC CSD slope as derived by Meech et al. (2004), suggesting that the process of splitting has an underlying physical mechanism that is different from the primary evolutionary processes (such as collisions and erosion) that affect kilometer-scale JFCs. It is important to note however that there is a size mismatch, so such a conclusion is tentative; there are no independent JFCs known to have nuclei as small as the fragments seen in 73P and 57P. Interestingly, both Meech et al. (2004) and Samarasinha (2007) have used simulations to suggest that the JFC CSD becomes shallower at sub-kilometer sizes due to a real dearth of such comets in the inner Solar System.

4.3 Comet 174P/Echeclus

The Centaur 174P/Echeclus = (60558) 2000 EC₉₈ was discovered by Spacewatch in March 2000 (Scotti et al., 2000), and it orbits between 5.9 and 15.6 AU from the Sun. Its current orbital intersection distance with Jupiter is 0.9 AU and with Saturn is just 0.2 AU; as a Centaur it is likely to be significantly perturbed on \(~10^7\) year timescales (Levison and Duncan, 1997) and may become a JFC. No cometary activity was reported for several years after its discovery, and physical properties of the bare object were obtained by several groups (Rousselot et al., 2005; Lorin and Rousselot, 2007; Stansberry et al., 2008). Activity was first noticed in December 2005 by Choi et al. (2006a) and continued through May 2006 (Choi et al., 2006b; Weissman et al., 2006), while the comet was about 13 AU from the Sun.

Bauer et al. (2008) present an analysis of contemporaneous ground-based visible and Spitzer infrared imaging of the comet from February 2006. Their images are shown in Fig. 5, and demonstrate why this comet should be counted

\footnote{Note that Fuse et al. (2007) call their “q” the CSD power-law slope but it is actually the differential size distribution’s slope; their \( 1 - q = -1.1 \) is the CSD slope.}
as one that has split. The center of brightness of the cometary activity is not on the nucleus itself, but offset (by six arcseconds at the time the images were taken). Furthermore there is a condensation embedded in the coma. However, imaging obtained in March 2006 (i.e. the following month) by Rousselot (2008) shows a more diffuse coma, and they state that the surface brightness profiles of the coma suggest that the dust is no longer coming from a central source but rather from a diffuse source.

One hypothesis to explain the observations is: Echeclus itself was mostly inactive, but perhaps active enough in one locale for a fragment to break off. This fragment stayed active, while the remainder of Echeclus continued to have no activity. After a few months, the fragment itself began to disintegrate into smaller pieces or subfragments. The subfragments remained active and so – at the spatial resolution obtainable from Earth – the coma appeared to emanate from a distributed source. The problem with this scenario is explaining why there would not be activity from the “hole” on the primary created by the departing fragment.

An alternate hypothesis is that we are seeing a satellite of Echeclus that just happens to be active. However, the motion of the fragment over the course of several months suggests that it is moving hyperbolically (Choi et al., 2006b; Weissman et al., 2006). The apparent motion is too great for a bound orbit, given the expected mass of Echeclus. Also, Echeclus’s Hill sphere radius at the time was roughly only $5 \times 10^4$ km, i.e. about 6 arcsec on the sky. Further evidence against the satellite hypothesis is that a search in earlier deep imaging (when no activity was seen) yielded no such object (Rousselot, 2008).

The fragment itself could be a few kilometers in radius (Rousselot, 2008) – compared to the $\sim 40$ km of the primary – and so a large impulse would be needed for that much mass to be accelerated up to the $\sim 15$ to $30$ m/s required to reach escape velocity. While typical separation speeds are an order of magnitude smaller (Boehnhardt, 2004), we note that a fragment that is flung off the surface of Echeclus due to the primary’s rotation could be given such a speed, since in that case the fragment’s speed would be proportional to the primary’s radius. On the other hand, current evidence suggests that Echeclus has a relatively long rotation period of 27 hours (Rousselot et al., 2005).

While a fragment remains the best explanation for 174P, further study of this enigmatic comet is certainly warranted. The main science goals would be to (a) ascertain the nature of Echeclus’s activity so as to explain how such a large mass could have left the primary; (b) explain why activity is so tightly localized; (c) determine what the source of the activity is (CO? CO$_2$? crystallization of amorphous H$_2$O ice?) and whether this plays a role in making fragmentation more likely; (d) monitor the rest of the Centaur population to determine whether any other objects suffer these events, and...
what the frequency is; and (e) infer what Centaur fragmentation implies for
the bulk structure and strength of the JFCs that the Centaurs become.

4.4 Short-Period SOHO Comets

The SOHO spacecraft has discovered over 1500 comets, almost all of which
are “sungrazers” (comets with perihelia less than about 0.06 AU). A large
fraction of the SOHO comets are part of the Kreutz family, whose comets
pass only about 0.005 AU from the center of the Sun. Since the Sun’s radius
is 0.00465 AU, many Kreutz comets (and almost all the ones discovered by
SOHO, which are faint) disintegrate to dust very near perihelion if not earlier.
The Kreutz comets are all presumably fragments of a long-period comet that
broke apart thousands of years ago; see Marsden (2005a) for a recent review.

Since the Kreutz comets are of long-period, we do not consider them here.
However SOHO has discovered four other families of sungrazer comets, some
of which may be of short-period. While the Meyer group (Meyer, 2002) comets
have orbital inclinations of about 72°, well out of the ecliptic, the Marsden
group (Marsden, 2002b), the Kracht group (Kracht, 2002a), and the Kracht
II group (Kracht, 2002b) have members with inclinations of 27°, 13°, and 13°,
respectively, perfectly normal for short-period comets. As with the Kreutz
family, the members of each group have similar orbits and thus imply a single
progenitor in the past. The perihelia of these comets are at about 0.05 AU,
so, while not currently passing within the Sun’s Roche limit, perhaps stress
due to tidal forces or due to energy transport facilitated fragmentation at
higher heliocentric distances. Such distant fragmentation has been suggested
by Sekanina (2002) for the Kreutz comets.

Recent work incorporating the 12-year database of cometary astrometry from
SOHO has revealed possible linkages between some of the comets in these three
groups, as well as between some comets not belonging to any known group.
This information is collected in Table 2. It is worth noting that the linking of
apparitions with short-arc orbits can be difficult, especially when independent
comets move on similar orbits anyway. There are several other possible links
among comets within the three groups that have been reported (e.g. Marsden,
2006; Kracht, 2008). Sekanina and Chodas (2003) present a detailed analysis
of some of the Marsden and Kracht group linkages.

Detailed physical studies of the sungrazing short-period comets are currently
limited to observations by Sun-staring spacecraft. These often provide mag-
nitudes and thus some secular light curve. In many cases, the comets are
sufficiently faint that neither a tail nor an extended coma is visible, limiting
the amount of available information on gas and dust. The nuclei are probably
of order dekameters in radius \cite{Marsden2005a}; this means that even with an improved orbit, it would be feasible to observe such a comet well away from the Sun only when it is near Earth. For example, a 10-meter radius nucleus at opposition 0.1 AU from Earth still only achieves an R-band magnitude of 22.5. So even in a very favorable apparition (which would not happen very often to begin with), it will not be easy to make detailed studies of such comets. The detailed study of a wide sample of sungrazing short-period comets will probably have to wait for very deep and wide sky surveys, or for classically-scheduled time at the largest telescopes.

4.5 Cometary Debris

As comet 73P shows, comet fragments have a distribution of sizes. Indeed, Fig. 1 demonstrates that such a comet gives off fragments that are decimeter sized and larger – fragments that are larger than what can be typically lifted off a comet’s surface simply by gas drag \cite{Gruen1990}. These fragments remain in a trail in the orbit plane since radiation pressure acts slowly on them.

The deep infrared observations by IRAS brought to light the existence of cometary debris trails \cite{Sykes1992}, consisting mainly of millimeter and centimeter sized grains that are the largest solid bodies that come off the comet during “normal” activity. Such grains have often been found to contain most of the mass that is contained in dust. The grains in the trails represent an intermediate size scale between the visible-wavelength dust that is typically micron sized and smaller, and observed fragments that are dekameter sized and larger.

An infrared survey of debris trails has been performed by Spitzer. \cite{Reach2007} present 24 \( \mu \)m imaging of 34 JFCs in which a trail is unambiguously seen in 27 of them – about 80%. Most of these comets were observed while 2 to 4 AU from the Sun, and months away from perihelion. Examples of the observations presented by \cite{Reach2007} are shown in Fig. 6.

Most of the comets in their survey had not suffered splitting events in the traditional sense; the particles were liberated by regular cometary activity. One could call these millimeter and centimeter sized particles “fragments” only in a liberal definition. Nonetheless, the high frequency of trails, coupled with the fact that often the trail was seen all the way out to the edge of the field of view, indicates that JFCs are prodigious producers of millimeter and centimeter sized fragments into the interplanetary dust environment. As \cite{Reach2007} point out, the total mass of these large grains is larger than the total mass of grains seen at visible wavelengths.
4.6 Searches for Fragments

Usually fragments are found serendipitously, but a few pointed searches for fragments have been performed. The survey of Chen and Jewitt (1994), mentioned earlier, focussed on finding fragments near (i.e. a few arcminutes away from) the primary comet. The faint meter and dekameter scale objects could have been missed, however. Beech et al. (2004) did a telescopic search for meter-sized (and larger) Perseid meteoroids while Earth was passing through the meteor stream; this would have detected fragments of the Halley-family comet 109P/Swift-Tuttle. They sought to find objects a few arcminutes away from the radiant before they collided with Earth’s atmosphere. The search found no objects, thus constraining the space density of meter-scale objects within the stream.

Another survey has made use of the proliferation of CCD cameras with very wide fields-of-view. Stevenson and Jedicke (2007) have used the Megacam instrument on the CFHT telescope atop Mauna Kea to search for fragments up to half a degree away from a comet’s head. They have observed about 12 JFCs so far with no fragments seen to a limiting magnitude of about 24. For these comets this limit corresponds to fragments of size about 100 m in radius. With such a large field-of-view, the search is not just a snapshot in time, but actually tests whether these comets have had any splitting event in the previous several months. This kind of survey gives a more complete view of the fragmentation history and so should provide a good new measurement of the frequency of JFC splittings.

5 Concluding Remarks

The interested reader is encouraged to study the recent review of split comets given by Boehnhardt (2004). We have tried here to provide a summary of recent developments on the topic of split comets. But what does the future hold for our understanding of this phenomenon? While splittings caused by tides can be predicted if the comet’s orbit is known, the large majority of JFC splittings instead happen stochastically. Classically-scheduled observing runs will often fail to catch these events. Synoptic observations of comets however will in general be more fruitful for understanding the full evolution of a comet before, during, and after a fragmentation event; unbiassed and well-sampled datasets will be important.

It is possible that all-sky survey projects in the coming decade will indeed provide us with a great deal of such data. For example, Pan-STARRS and LSST will likely discover several hundred comets each in their first year of
operation in addition to the thousands of new Trojans, Centaurs, and trans-Neptunian objects they will find (Jewitt, 2003; Ivezić et al., 2008). In addition, the temporal coverage (scanning the sky on week-long timescales), depth (reaching approximately 23rd magnitude), and angular resolution will ensure that moderate-sized fragments of JFCs will be found more reliably. Furthermore, we will be able to follow the photometric and dynamic evolution of the fragments for months and possibly years at a time. The datasets will revolutionize our picture of fragment behavior and endurance (in addition to revolutionizing many questions about comets).

Since the review by Boehnhardt (2004) was published, the most important event with regard to split JFCs was the apparition of comet 73P/Schwassmann-Wachmann 3 in 2006. Following up other known split comets in the future would be worthwhile as well but 73P represents a unique case that is crucial to study. Observations of 73P in forthcoming years can give us new details about its fragments and its continuing evolution. If fragments B and C survive, we will be able to watch their new surfaces age as they continue to be exposed to the space environment. Will the resulting chemistry change the apparent production rates we measure in their comae? If so, how? Observations of other JFCs at multiple apparitions have shown a constancy in relative coma abundances from orbit to orbit (A'Hearn et al., 1995), but likely none of those comets have had such a recent fragmentation event that produced a secondary of comparable size to the primary. Physical observations of the continued unraveling of fragment B and perhaps the eventual unraveling of fragment C would also give us more insight into cometary structure. Unfortunately, three of the next five apparitions of 73P are unfavorable – only the visits in 2022 and 2033 are good – but even limited data on each fragment at each orbit would be useful.

More generally, wide-field observations of all JFCs that will make close approaches to Earth would be useful for understanding the frequency of fragmentation and the endurance of the fragments, since the proximity will make searches for meter-scale fragments feasible. For example, comet 103P/Hartley 2 approaches to 0.12 AU in 2010, and comet 45P/Honda-Mrkos-Pajdušaková comes to 0.06 AU in 2011.

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Table 1
Known Split JFCs

| Comet                          | When          |
|-------------------------------|---------------|
| 3D/Biela                      | 1840          |
| 16P/Brooks 2                  | 1889, 1995    |
| 51P/Harrington                | 1994, 2001    |
| 57P/du Toit-Neujmin-Delporte  | 2002          |
| 69P/Taylor                    | 1915          |
| 73P/Schwassmann-Wachmann 3    | 1995, 2001, 2006 |
| 79P/du Toit-Hartley           | 1982          |
| 101P/Chernykh                 | 1991, 2005    |
| 108P/Ciffreo                  | 1985          |
| 120P/Shoemaker-Holt 1         | 1996          |
| 141P/Machholz 2               | 1987, 1989    |
| 174P/Echeclus                 | 2006          |
| 205P/Giacobini                | 1896, 2008    |
| D/1993 F2 Shoemaker-Levy 9    | 1992          |
| P/2004 V5 (LINEAR-Hill)       | 2004          |

List adapted from work by Boehnhardt (2004).
Note that 174P is also a Centaur.
Table 2
Potentially Periodic Sungrazers

| Comets                      | Group    | $P$  | Refs. |
|-----------------------------|----------|------|-------|
| C/1999 J6 = C/2004 V9      | Marsden  | 5.49 | 1     |
| C/1999 M3 = C/2004 L10     | Kracht   | 4.95 | 1,2   |
| C/1999 N5 = C/2005 E4      | Marsden  | 5.66 | 3     |
| C/1999 N6 = C/2004 J4 or C/2004 J18 | Kracht | 4.81 | 1,2   |
| C/1999 R1 = C/2003 R5 = C/2007 R5 | Kracht II | 3.99 | 4     |
| C/1999 X3 = C/2004 E2 = C/2008 K10 | (none) | 4.22 | 5     |
| C/2000 O3 = C/2005 W4      | Kracht   | 5.32 | 6     |
| C/2001 D1 = C/2004 X7 = C/2008 S2 | (none) | 3.78 | 7     |
| C/2002 Q8 = C/2008 E4      | Kracht   | 5.52 | 8     |
| C/2002 R1 = C/2008 A3      | Marsden  | 5.37 | 9     |
| C/2002 S11 = C/2008 G6     | Kracht   | 5.54 | 10    |

All comets are named SOHO. $P$ = orbital period in years. References: 1 = Marsden (2004), 2 = Sekanina and Chodas (2005), 3 = Marsden (2005b), 4 = Marsden (2007), 5 = Marsden (2008d), 6 = Marsden (2005c), 7 = Marsden (2008e), 8 = Marsden (2008c), 9 = Marsden (2008a), 10 = Marsden (2008b).
Fig. 1. Mosaic of comet 73P/Schwassmann-Wachmann 3 as observed by the Spitzer Space Telescope over May 4 to 6, 2006, at a wavelength of 24 µm. About three dozen fragments of this split comet are visible here, and almost every one has its own cometary tail. The fragments themselves all lie on the comet’s projected orbit. Courtesy W. T. Reach of Caltech.
Fig. 2. Information about the fragments of 57P. At top are the 18 fragments discovered by Fernandez et al. (2002) on July 17, 2002. Each panel is 44 arcsec across. Short white segments indicate the location of each fragment. Note the wide variety of morphologies and condensations. At bottom is a schematic showing the location of each fragment with respect to the head - fragment A. The location of fragment B (Marsden, 2002a) is also shown.
Fig. 3. Hubble Space Telescope image of fragment B of comet 73P, taken on April 18, 2006 by Weaver et al. (2006). The fragment itself is the condensation at upper left; the image was taken just after the fragment had shed several fragments of its own. These are the dozens of condensations farther down the tail. The image is about 25 arcsec across, and HST’s spatial resolution is just 8 km/pixel (i.e. 0.05 arcsec/pixel). Courtesy H. A. Weaver of JHU APL.
Fig. 4. Detail of an image (after unsharp masking) of fragment B taken by Fuse et al. (2007) on May 3, 2006, with the Subaru telescope. The image is their Figure 1. The field size is 96 by 68 arcsec. Fragment B itself is in the upper left, and Fuse et al. (2007) report finding 54 fragments in the image. Compare the time and scale to Fig. 3. White streaks are trailed stars.
Fig. 5. Images of comet 174P from February 24, 2006, adapted from Figs. 1 and 3 in the work by Bauer et al. (2008). The left panel shows the R-band image from the Table Mountain Observatory 0.6-m telescope; the right shows the 24-µm image from the Spitzer Space Telescope. In each panel, the two arrows indicate the main body of Echeclus itself and the condensation of the coma. Note that the orientations are slightly different; in the TMO image, equatorial north is up, while in the SST image, north is 21° to the right of up.

Fig. 6. Spitzer images of four representative JFCs taken from the work by Reach et al. (2007a). Clockwise from top-left: 10P/Tempel 2, 48P/Johnson, 129P/Shoemaker-Levy 3, and 67P/Churyumov-Gerasimenko. All show a linear trail populated by millimeter (and larger) scale grains, though with different meridional and longitudinal variations. While some of the comet-to-comet variation is due to observing geometry, there are some intrinsic differences in the trails.