2. Weird Objects with Split Personalities

Asteroids Behaving Like Comets

Thus far, we have been speaking mainly about asteroids and their near relatives such as Kuiper belt objects and the like. But comets, which might be considered the "second cousins" of asteroids, have also been mentioned on quite a few occasions, so now we must ask the question, "What is the difference – the real or essential difference – between an asteroid and a comet?"

The usual answer runs something like this. Comets are bodies that contain a more or less large quantity of ice and other volatile materials and it is through the sublimation of these materials that they release gas and dust as they come closer to the Sun and receive more solar heat. Asteroids, on the other hand, are composed of non-volatile materials such as rock and metal and therefore remain stable even if they should venture near to the Sun and their surfaces become very hot.

That is not a bad explanation of the difference between these two classes of celestial body, however it raises questions if we examine it more closely. For instance, where does one draw the line between what is "non-volatile" and what is "volatile"? There is a subtle, subjective bias in these terms. The truth of the matter is that, given enough heat, *anything* will vaporize, so in a sense there is nothing that is truly non-volatile! There is only a distinction in so far as some arbitrary level of temperature is chosen to differentiate those substances that we deem to be volatile and those that we deem not to be. But notice that it is "we" who do the deeming. There is not some great divide in nature separating two intrinsically different classes of material. And, of course, because it is "us" who decide which substances are and which are not volatile, the line that "we" draw is one that is approximately the temperature where our form of life is possible. In short, the dividing line is more or less the

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temperature of water under the conditions prevalent at the surface of Earth. Substances that remain solid when heated past the boiling point of water are thought of as being non-volatile while those that are already gaseous at water's freezing point are considered volatile. Yet, if we could imagine intelligent beings on Saturn's moon Titan, they would surely have a different notion of what "volatile" and "non-volatile" (or the Titanian equivalent of these terms!) mean. For them, water would be non-volatile rock. Methane would probably define the division between the volatile and the non-volatile. At the other end of the scale, if our imagination could stretch even further to imagining intelligent life on those recently discovered star-hugging extrasolar planets whose surfaces are covered by oceans of molten rock, the definition of "volatile" might be anything with a melting point below that of elemental titanium!

Perhaps a more general and less biased way of dividing comets and asteroids is by the observed behavior of the object in question. In short, to make any "activity" exhibited by the object the basis of classification. If the body of concern is active in the sense of shedding material into surrounding space, it is a comet. If it is not, it is an asteroid. That sounds nice and simple and was essentially what Dr. Brian Marsden had in mind when he said, "If it has a tail, it is a comet". In fact, if it has a coma, it is a comet, whether a tail is present or not. At least, that was always the traditional approach. If something fuzzy or sporting a tail was found, it was automatically announced as a new comet.

But a closer look at the subject brings complications, as all "closer looks" are wont to do! For a start, if "activity" in this context is defined as shedding material into surrounding space, just about every object in the universe becomes a comet! Think about it for a moment. Stars shed material, planets lose atoms from their atmosphere to surrounding space and even have them swept away by the solar wind in much the same manner as the ion tails of comets. Even "inert" asteroids lose a little matter to space courtesy of meteoroid impacts and maybe even electrostatic elevation of fine dust particles that get swept away—dust-tail fashion—by the pressure of solar radiation. And if an object sporting a tail is automatically listed as a comet, then how are we to classify the planet Mercury following the observation of a tail of sodium sported by this object and recorded in STEREO images? Sodium tails similar to this have been observed on a number of comets, most notably the spectacular object C/1995 O1 (Hale-Bopp) during the peak of its display in 1997.

Perhaps we should limit "activity" to observable activity exhibited by small objects, where "small" means anything from several meters to a few hundred kilometers in diameter. But even then we run into trouble. What actually does "observable" mean? With what are we supposed to have observed the vital activity? These questions have become relevant in recent times, as we shall see a little later, in so far as some objects that had been classified as asteroids have been found to display activity that is definitely of a cometary nature, but so weak that it can only be detected by other than visual means. By all methods of observation available to astronomers a century ago—or even less—bodies of this nature would have appeared totally inactive.

Most people will surely agree that the detection of any activity (irrespective of how feeble) by any means is enough to justify the reclassification of an apparent asteroid as a comet, although we might wish to prefix "comet" with some modifying phrase such as "low activity", "nearly defunct" or the like. Whether there is a line beyond which even these qualified designations are not deemed suitable—whether there is a level of activity which, although detectable by sensitive instruments, is considered to be just *so* low that an asteroid displaying it is still thought unworthy of comet status—has not yet been tested (unless we consider Ceres to qualify for being one such object!).

Another issue that has been brought to the fore in recent years—actually since 2010 following the discovery of P/2010 A1—is the nature of the activity of an object and whether, or to what degree, this determines if something should be classified as a comet. The issue here is whether only a certain type of process driving the "activity" giving rise to a coma and/or tail should be considered as truly cometary. Overlooking the deeper issue raised earlier as to what is to be deemed volatile material ("ice") or non-volatile material ("meteoric matter" as it is usually denoted) several decades ago it was established that cometary activity of the typical—what we might call "classical"—variety is driven by the sublimation of water ice and various frozen gases as the body draws closer to the Sun and reaches higher surface temperatures. The gases emitted and the particles of rocky and organic material released from the "dirty ice" conglomerate and propelled away from the cometary nucleus by the expanding gases is what constitutes the coma and tail of the "classical" comet. However, we now know that other processes not involving sublimating ices can also give rise to coma-like clouds surrounding small bodies and can even manifest as comet-like tails under certain circumstances.

According to astronomer David Jewitt, there are six processes, other than the regular sublimation of ices, that may give rise to comet-like features associated with small objects. Some of these are more likely to be realized in nature than others and some are more likely to result in repeated episodes of activity. The processes are as follows:

1. Impact-triggered sublimation of underlying ice. This is not so much an alternative to the "classical" process as a special instance of this process. What is envisioned here is a hitherto inactive body (either an "ordinary" asteroid that nevertheless possesses a quantity of subsurface ice, or a comet nucleus that has become totally covered by insulating material, preventing any vestige of its former activity from still occurring) being struck by a large meteoroid, resulting in either the splitting of the body or the creation of a large impact crater on its surface. Either way, quantities of ice, previously deeply buried, are exposed to solar warmth, resulting in sublimation.
2. Impact of a non-icy body by a large meteorite or even a collision between two asteroids of approximately equal size. The dust and debris raised by such an event can swell out into a very comet-like coma and tail. The asteroid collision scenario seems first to have been proposed by E. Barnard back in 1893/1894 to explain the sudden appearance of Comet Holmes. We now know that he was incorrect in using this as an explanation for the Holmes outbursts, but he was correct in seeing asteroid collisions as being possible sources of comet-like phenomena.
3. Electrostatic repulsion may also contribute to the expulsion of dust from asteroidal bodies. Dust is known to be levitated on the Moon due to the electrostatic charge gradients that result from uneven solar illumination. Regions that are sunlit—which actually means exposed to the whole spectrum of solar radiation on the atmosphere-less Moon—lose electrons which fly away from these areas and gather in the shadowed regions, such as the shadows of mountains, within craters and, most impressively, across the day/night terminator. The latter appears to be

accompanied by a permanent, moving, dust storm which, although of very low density compared with dust clouds on Earth, is nevertheless sufficient to give rise to unexpected twilight effects imitating the crepuscular rays seen in terrestrial sunrises and sunsets. These effects were reported by the Apollo astronauts, who must have been hard pressed to believe their eyes after seeing twilight phenomena on a body supposedly devoid of atmosphere! Dust raised by this means on the Moon cannot escape lunar gravity; however a similar process on small asteroids, especially those that make close approaches to the Sun, may result in the expulsion of fine dust in a process closely mimicking "classical" cometary activity.

4. Objects that rotate very rapidly can, theoretically, shed loose material from their surfaces or even become completely disrupted. Asteroids that are loose rubble piles having little overall tensile strength are likely to be prone to such rotational bursting. This process can take place in comets as well and is believed to have been responsible for the fragmentation of 332P/Ikeya-Murakami prior to its 2016 apparition.
5. Thermal fracture can also occur in asteroids that have small perihelion distances. This takes place when expansion stress of surface materials exceeds the tensile strength of the expanding material. Hydrated materials such as clays, serpentine and so forth can lose trapped water when they are heated, causing fracturing and desiccation such as that seen in the cracked mud of sunbaked lakes on Earth. Temporary instances of this process can also be caused by impact heating, so it might be relevant even for some asteroids that do not closely approach the Sun.
6. It is also possible that radiation pressure might waft small particles from kilometer-sized asteroids passing very close to the Sun. Impacting particles of solar wind may be included here and it has been suggested by at least one astronomer that atoms knocked out of asteroid surfaces by intensified solar radiation during times of heightened solar activity might be responsible for generating weak plasma tails. The latter speculation is probably unlikely and this general effect is probably only a minor one on its own. However it is possible that it may work in tandem with some of the other processes already mentioned. The rotational, thermal and electrostatic effects seem especially open to the assistance of radiation pressure.

More than one of these processes may operate together in any particular instance, as suggested especially for number 6.

Now, it is all very well to speculate about what processes might mimic "classical" cometary behavior, but do they really occur in nature? The answer to this question is "Yes"; at least some of the processes mentioned appear to best explain the weird "non-classical" comets (dare we still call them "comets"?) that have been observed in recent times. Let us now look at some of these weird bodies.

Comet Elst-Pizarro and Its Relatives

Back in 1979, M. Hawkins, R. McNaught and S. Bus found an asteroid in the outer regions of the main asteroid belt. That hardly made for stop-press news. Main-belt asteroids are so numerous that new ones are being found all the time, so this was simply designated as 1979 OW7, and with later observations and improved orbital computations, given the permanent designation of 7968. Little more attention was given to this object.

Then, in 1996, E. Elst and G. Pizarro found images of a comet sporting a long and thin tail, but with a curiously "asteroidal" looking head. That is to say, the head appeared to be quite star like, without obvious evidence of a diffuse coma. The somewhat odd appearance of the comet was, however, as nothing when compared with the surprise awaiting the derivation of its orbit. The new comet turned out to be identical with the apparently very ordinary asteroid 1979 OW7.

At first, astronomers wondered if this object was a "real" comet at all or if what seemed to be a tail was actually a trail of debris thrown up by an impact between the asteroid and a large meteoroid. Their explanation for this apparent comet ran parallel with the speculation made by Barnard just over a century earlier as to the nature of Comet Holmes. This hypothesis appeared very reasonable; however analysis of the tail by Z. Sekanina indicated that its constituent particles had been emitted by the object over a period of time, as would be expected for "classical" cometary activity, and not in a single burst as would be implied by a meteorite impact. Moreover, Elst-Pizarro (as it was subsequently named) has now been observed at several perihelion passages, and on each occasion it sprouts the same type of tail as observed in 1996. Clearly this activity is a regular feature of this object and not some freak occurrence that happened in that year alone.

The object seems to be a "true" comet. But what is a comet doing in an apparently stable asteroidal orbit? Asteroids inhabiting the main belt have been there essentially since the formation of the Solar System and there was no question that the amount of ice contained in an object as small as Elst-Pizarro would have been exhausted long ago. A comet simply could not remain active in a short-period orbit for billions of years!

The suggestion was raised that this body may once have been a member of Jupiter's family of periodic comets, but somehow dynamically evolved into an asteroidal orbit. In that scenario, Elst-Pizarro is a recent arrival in the asteroid belt and its continuing activity ceases to be a mystery. Nevertheless, the supposed dynamical pathway from a Jupiter-family comet to a stable asteroidal orbit is not at all clear.

A clue to the solution of the mystery came, however, by comparing the orbit of this object with other asteroids in the outer belt. It turns out that Elst-Pizarro (asteroid 7968 Elst-Pizarro, aka 133P/Elst-Pizarro) is a member of the Themis asteroid family. This is a large family of dark asteroids that presumably originated in the (probably collisional) breakup of a large carbonaceous asteroid some time in the distant past. Within the broader Themis family, there exists a smaller sub-family associated with the asteroid Beagle. This Beagle family is considerably younger than the Themis family per se and presumably originated when two of the Themis asteroids collided some time during the last ten million years. Elst-Pizarro, it is of interest to note, is a member of the Beagle family of Themis-family objects.

Now, it is hardly possible that Elst-Pizarro has been active at each perihelion passage during the past ten million years, but it is reasonable to expect that the asteroid disruption that gave rise to the Beagle family would have left many of the fragments with ice very close to their surfaces and that a recent small impact with a meteorite may have been enough to expose a fresh patch of ice sufficient to drive cometary activity at perihelion. That appears to be the most reasonable explanation for the activity of this object. Furthermore, the presence of ice has been confirmed on the "patriarch" of the Themis family; the asteroid Themis itself. No cometary activity has been suspected in association with this asteroid, but the presence of ice at least would seem to give it a certain "cometary potential". Maybe sensitive space-based observations will one day discover the presence of very weak activity on Themis—unless a meteorite impact activates it in Elst-Pizarro fashion in the meantime!

The years since Elst-Pizarro was discovered have brought forth quite a crop of discoveries of bodies that bridge the apparent gulf between comets and asteroids. By the latter half of 2016, more than 20 such bodies had been listed, although not all of these were denizens of the main asteroid belt and not all displayed the same type of activity found in Elst-Pizarro, as we shall shortly see. Nevertheless, several of these objects are almost certainly of a similar type to this comet and, probably significantly, a disproportionate number of these have been linked with the Themis family.

In saying this, however, it should also be noted that gaseous emission has not as yet been observed in any of these bodies, including Elst-Pizarro. Thus, while the exposure of internal ice and its subsequent sublimation is widely considered to be the source of their activity and the lack of observed gaseous emission is believed to be due simply to the small amount of gas emitted, it would make a nice confirmation of this hypothesis if gas was actually observed!

Colliding Asteroids and "Temporary Comets"

On January 6, 2010, the LINEAR program discovered a small comet with a clearly defined tail. There was nothing unusual about this of course, LINEAR had by then found many comets, but this one turned out to be anything but usual. Precise positions obtained following discovery revealed that this object was one of very short period, less than four years in fact, but even more peculiar was the fact that its orbit had a low eccentricity and was confined to the inner regions of the asteroid belt. It was clearly a "main-belt comet", but differed from other members of its clan (Elst-Pizarro for example) by lying within a region of the main belt principally populated by S-type stony asteroids rather than the dark carbonaceous bodies typical of the Themis family and the majority of the other denizens of the outer belt. Further comparison of the new object's orbit with those of other inner asteroids indicated that P/2010 A2 (LINEAR) (as it was duly designated) is a member of the Flora asteroid family. The large asteroid 8 Flora itself, the principal member of this rather populous family, is an S-type asteroid and, presumably, 2010 A2 is of similar composition. That would make it a most peculiar comet!

Closer examination of the tail of the comet made this object seem even stranger. There was no true "nucleus" or central condensation at the point of the tail and no coma in the usual sense of that word. Instead, there was a roughly X-shaped structure and, offset from the central point and away from the projected axis of the tail, a small asteroidal object estimated to have been approximately 140 m in diameter (Fig. 2.1).

What was really happening here?

Most astronomers agree that this object is not a "comet" in the usual, "classical" sense of the term. In other words, it is not an

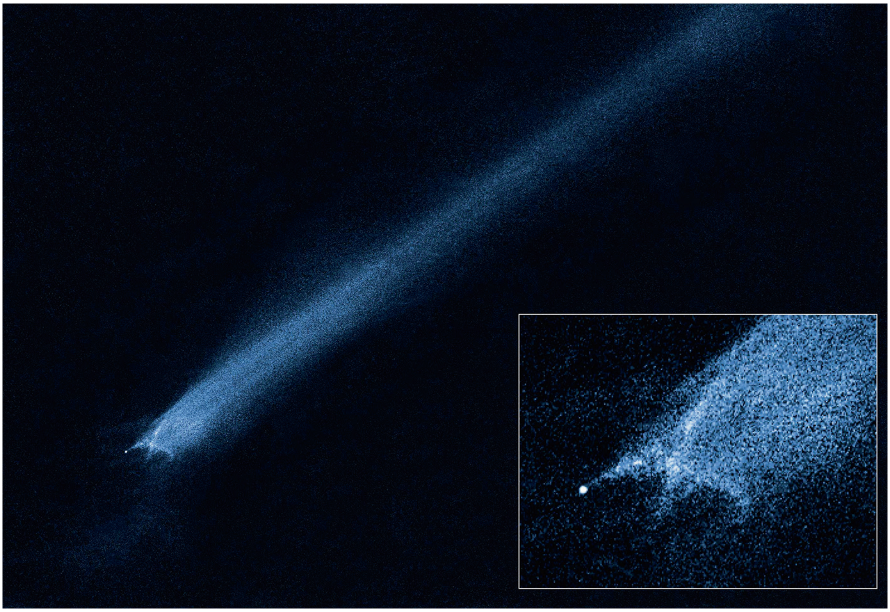

Figure 2.1 Comet/asteroid P/2010 A2 (LINEAR), January 27, 2010. Credit: Hubble StScl-2010-07/NASA/ESA/D. Jewitt (UCLA)

icy body experiencing some of its mass sublimating into surrounding space. Instead, it appears to be a rocky asteroid that for some reason shed material in a brief burst, imitating a true comet for a brief while, but for reasons other than the presence of sublimating volatile material. Most probably, this small asteroid was struck violently by a second body, releasing a large amount of dust, the finer particles of which were then swept away by the pressure of sunlight into the comet-like tail. The "collision" scenario, once proposed unsuccessfully as an explanation for the activity of Elst-Pizarro and, long before that, for the outburst of Comet Holmes, had finally come into its own! It has also, however, been suggested that the partial breakup of this body may have resulted, not through a collision, but because its rotational velocity had increased to the point where it literally flew apart. This process, as we shall soon see, does occur, but a major collision appears to be the more probable culprit in the present case.

D. Jewitt estimates that impacts involving asteroids happen quite often, probably once a year on average, or maybe even more frequently. In the 2010 A2 instance, the impacting body was probably not very much smaller than the main asteroid itself and the velocity of impact was likely to have been around 9400 miles (15,000 km) per second—roughly five times the speed of a rifle bullet. The force of the resulting explosion would have been considerable, liberating more energy than a nuclear bomb.

As if to prove Jewitt's point about the frequency of asteroidal impacts, a second event was observed later that same year. On December 11, 2010, S. Larson at Catalina found the long-known asteroid 596 Scheila to be surrounded by what looked like a cometary coma. Follow-up observations by astronomers using the Faulkes Telescope North found that it was also sporting a linear tail stretching away in the anti-solar direction as well as a dust trail extending along its orbit. The former was composed of fine dust particles driven away from the asteroid by solar radiation pressure, whereas the second betrayed the presence of relatively large particles upon which radiation pressure would have had little repulsive effect and which simply spread back along the asteroid's orbit (Fig. 2.2).

The asteroid had been known for many years, having been discovered by A. Kopff as long ago as 1906 February 21, but had not

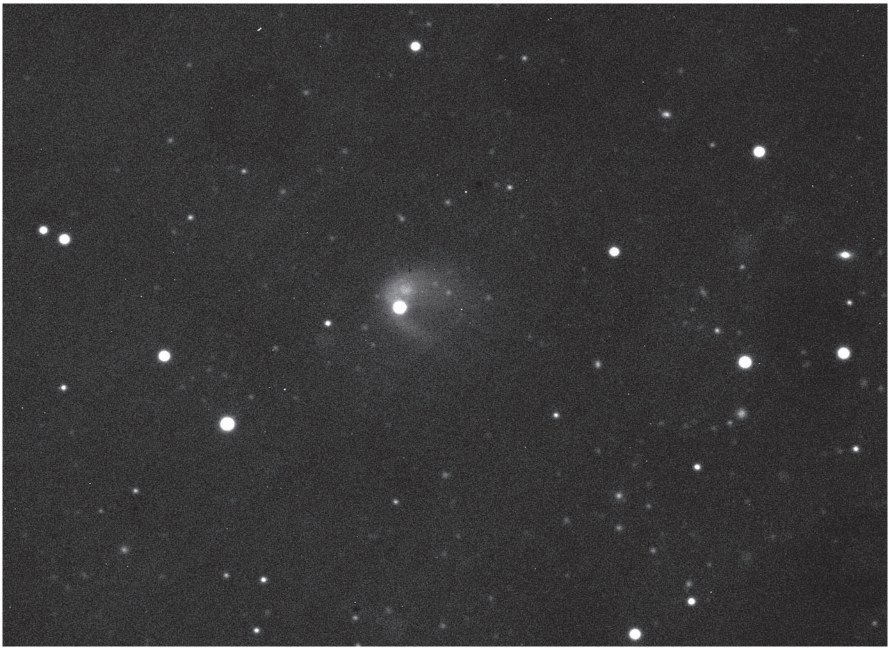

FIGURE 2.2 Active asteroid 596 Scheila imaged on December 12, 2010 with the 24-in. telescope at Light Buckets in Rodeo, NM. Credit: Kevin Heider

previously been seen to display any comet-like activity. Moreover, no gas was evident in the spectrum of the coma, so it seems that only dust was released during the outburst of 2010. The most probable explanation is that the asteroid had been struck by a body having a diameter of around 35 m.

A similar event appears to have taken place in March 2015 concerning the asteroid 493 Griseldis. This body was found to be sporting a tail-like feature in images secured using the 8-meter Subaru telescope and subsequently confirmed by images taken with other large telescopes both in Chile (the Magellan Telescope) and in Hawaii. The feature was apparently very transitory however and did not show up on images secured in April. An impact is the most probable cause of this activity, however it should also be noted that Griseldis is classified as a P-type body, a class of asteroid believed closely related to carbonaceous bodies and broadly similar to cometary nuclei. Therefore, it is just possible that the 2015 activity of this body may have involved sublimation of volatiles (maybe the bursting of a small subsurface pocket of gas?) and it will be interesting to see whether the asteroid displays any similar activity in the future.

An interesting instance of a similar asteroidal disruption to that proposed for P/2010 A2 is implied by some curious observations of the asteroid 2201 Oljato. These observations probably betray an earlier collision between this asteroid and a second body, although it is also possible that thermal stress may have had a role to play in this incident.

During the 1980s the *Pioneer Venus Orbiter* observed what appeared to be the vestiges of cometary activity associated with this body. This spacecraft observed three passages of the asteroid between Venus and the Sun and on each occasion it recorded a marked increase in peaks of a type of unusual magnetic disturbance known as Interplanetary Field Enhancements or IFEs. These occurred both ahead of and behind the asteroid and were interpreted by some as evidence that Oljato was really a very weakly active comet. Visually, its appearance was asteroidal, but the presence of the IFEs seemed to imply the existence of a low level of dust emission from the body into what might, perhaps, be thought of as a sub-visual dust tail or, more correctly, a sub-visual debris *trail*. Some astronomers suspected that Oljato had once been a true comet. However, this suggestion encountered difficulties when it was discovered that the reflectance spectrum of this body, despite some peculiarities, was indicative of a rocky asteroidal composition rather than a characteristically icy cometary one.

The situation became even weirder in 2012. That year saw *Venus Express* arrive at the planet and, like its predecessor, this spacecraft also observed several passages of the asteroid. However, in strong contrast to the earlier Orbiter, Venus Express failed to observe *any* IFEs associated with passages of Oljato. Even stranger, the rate of these disturbances in the regions immediately behind and ahead of the asteroid was actually *lower* than the average! What could possibly be happening here? Had the "comet" become completely defunct sometime between 1980 and 2012? Had Pioneer Venus Orbiter actually been privileged to record the terminal breaths of a dying comet?

A more convincing explanation not involving cometary activity in the "classical" sense, was given by Dr. C. Russell. According to Russell,

> At one point in time Oljato shed boulders – mostly a few tens of meters in diameter – into its orbit and they formed a debris trail in front and behind Oljato. These impactors then hit other targets as they passed between Venus and the Sun. The large amount of fine dust released by these collisions was picked up by the solar wind, producing the IFEs observed by Pioneer and was accelerated out of the Solar System.
>
> The reduced rate of IFEs observed during the Venus Express epoch suggests that the collisions with Oljato's co-orbiting material have reduced the general debris in the region as well as the co-orbiting material shed by Oljato.
>
> The IFEs observed by Pioneer suggest that more than 3 tonnes of dust was being lost from the region each day. Effects associated with solar heating and gravitational perturbations have gradually nudged larger chunks of debris from Oljato's orbit. From once being unusually crowded, the region has become unusually clear and free of IFEs.

It would appear that, in the manner of P/2010 A2, Scheila and (probably) Griseldis, Oljato underwent a burst of "non-classical" cometary activity at some time in the recent past. Although disruption resulting from thermal stress may have been the cause, the more likely culprit was a large meteoroid crashing into the asteroid. For a time, Oljato presumably sported a dust coma and tail and, had it been observed at that time, would have appeared very comet-like, maybe resembling 2010 A2 or possibly Scheila in 2010. What was observed in the 1980s was simply the final act of the asteroid's temporary performance.

Rotational Instability as a Cause of "Cometary" Activity in Asteroids

The years 2012 and 2013 saw the discovery of three very strange "main belt comets" or "active asteroids" whose activity was due neither to the sublimation of ice nor the impact of other bodies but almost certainly to instability caused by their rapid rotation.

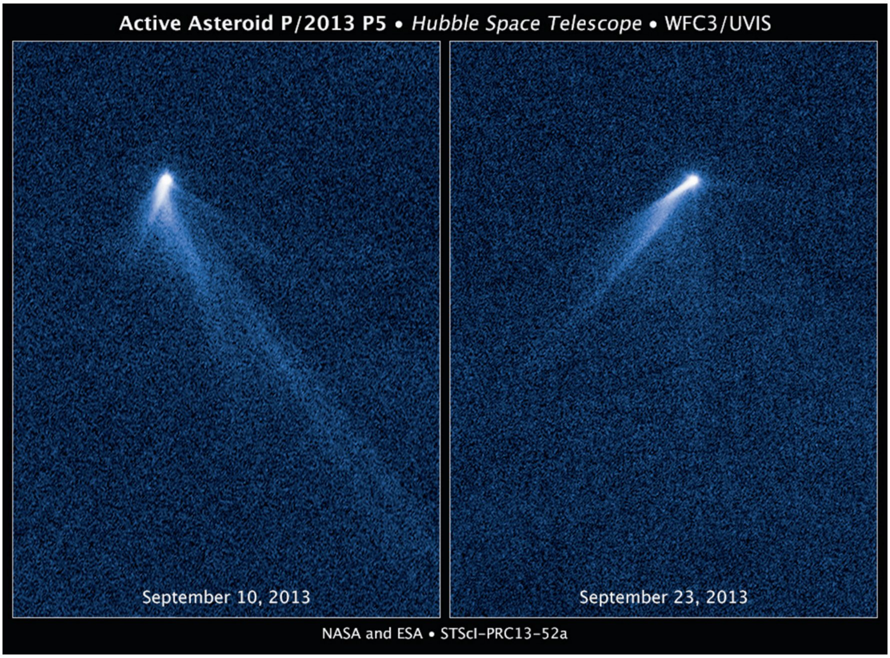

FIGURE 2.3 Active asteroid P/2013 P5 imaged by the Hubble Space Telescope. Credit: NASA/ESA/D. Jewitt (UCLA)

The first of these, and the least extreme of the two, was P/2013 P5 (PANSTARRS) or, to give it is final designation and name, 311P/PANSTARRS. It was discovered on 27 August, 2013 and was notable in that it sported six clearly defined tails. No gaseous emission was noted however and the tails were all composed of dust. Closer examination of this object indicated that it was not really a "comet" in the narrow sense of that term (despite its multi-tailed appearance) but a small asteroid, just 790 ft. or 240 m in diameter, that was spinning so fast that particulate matter comprising its regolith was being flung off into surrounding space. The loose regolith material had probably been built up over a period of time through the constant impacts of small meteoroids and dust particles (Fig. 2.3).

This object—call it "asteroid" or "comet" depending on your choice—did manage to remain intact however. At least, it has not disrupted as yet! Nevertheless, the same cannot be said for the second "active asteroid" discovered during the latter months of 2013. This one—officially designated as P/2013 R3

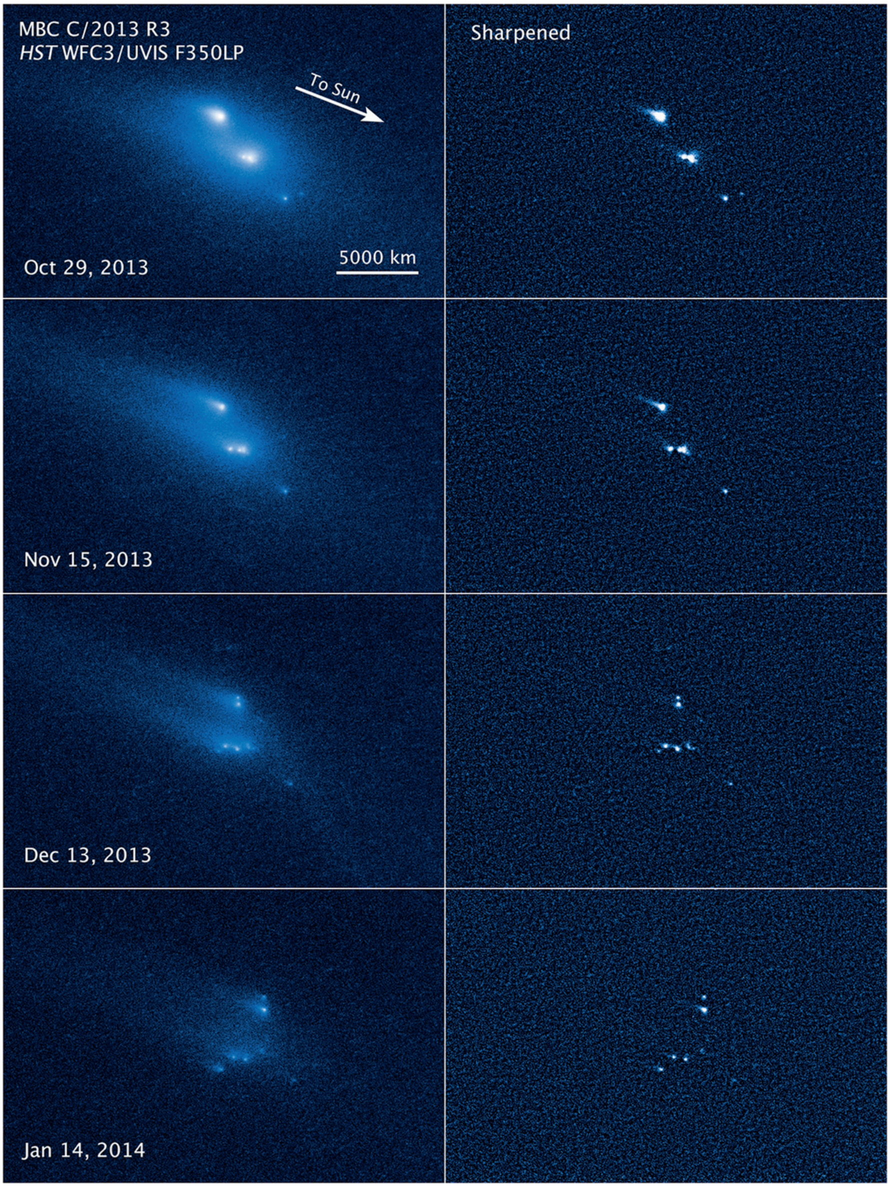

FIGURE 2.4 Disintegration of asteroid/comet P/2013 R3 as imaged by the Hubble Space Telescope. Credit: NASA/ESA/D. Jewitt (UCLA)

(Catalina-PANSTARRS) was first located on September 15, 2013 and found to be following an orbit of low eccentricity typical of asteroids in the outer regions of the main belt. Its distance from the Sun remained close to 3 AU throughout its orbit (Fig. 2.4).

The new object was clearly active, but the strangest thing about it was that it was just as obviously breaking up. Fragments were observed drifting away from the main mass and a great deal of dust was being released. But the reason for this was not immediately obvious. The comet (let us call it that for want of a better description) was not passing close to a planet (nor had it recently done so) and it was certainly not passing close to the Sun. It had, therefore, not experienced the sort of tidal or heat stress that might be capable of disrupting a solid object. No gaseous emission was observed, so an eruption of a pocket of some very volatile material would also seem to be ruled out. Sublimation of water ice likewise appeared to be an unlikely cause, as at the comet's distance from the Sun, this would only sublimate slowly and could do little damage. As David Jewitt expressed it, water-ice sublimation at that distance from the Sun "would not produce enough pressure to fracture a pile of talcum powder". One might suspect that this may have been another instance, akin to P/2010 A2, of an asteroid collision, however continuing observations of the event indicated that the disruption was a process that continued over time and not a sudden breakup of a solid body, as would be expected to result from an impact.

The real culprit, as with 311P/PANSTARRS, was almost certainly rotational instability. For this object however, the rapid rotation did not simply fling loose regolith material off the surface of the nucleus, but actually caused the "nucleus" (or "asteroid" if that term is preferred here) to literally fly apart. In other words, this appears to have been an instance of an asteroid being destroyed, by the process of centripetal disruption, right before the eyes of terrestrial astronomers!

Objects such as 311P and 2013 R3 probably reached the critical velocity of rotation, at least in part, through the action of the so-called Yarkovsky effect. Briefly stated, this effect refers to the fact that solar radiation illuminating the sunlit hemisphere of a rotating object is partially absorbed by that object and reradiated again into the sink of space as the object turns on its axis and the formerly daylight regions turn away from the Sun. As the absorbed energy is radiated back into space, a slight force is exerted on the object, just as it would if particles of matter were being emitted from its night side. This non-gravitational effect is negligible for large objects, but can make its presence felt on meteoroids and asteroids smaller than about 10 km in diameter. The Yarkovsky effect has been observed as a non-gravitational influence affecting the orbital motion of some well observed small bodies. The influence of the process on their rotational velocity can also build up over time and cause small asteroids to reach rotational velocities sufficiently great for disruption to occur. Jewitt has even suggested that rotational instability may lead to the destruction of more small asteroids than meteorite impacts and asteroid collisions.

But why did P/2013 R3 fly apart whereas 311P remained intact? Most probably, R3 has a rubble pile constitution with very little cohesion while 311P may be a single monolithic body having greater tensile strength. Observation of the color of R3 is suggestive of a C-Type asteroid, which may imply an initially relatively weak body that has been broken apart by impacts in the more or less distant past. Assuming these impacts to have been of low velocity, the numerous fragments into which the original body had been broken then came together again into a loosely constituted rubble pile which was more vulnerable to rotational disruption than a single solid and rocky body would be. The discovery, in quick succession, of these two objects in 2013 therefore provided astronomers with a good pair of examples displaying the range of effects induced by rotational instability.

Another object which may have fallen victim to rotational instability is 331P/Gibbs. On September 18, 2012, this object was found to exhibit a definite dust trail and deep images taken in 2014 revealed the presence of four faint condensations embedded within an orbit-aligned dust trail. These deep observations also revealed the object to be rotating rapidly with a period of just 3.24 h, so rotational instability may have been responsible for the observed disruption and dust emission. Nevertheless, the form of the trail also suggested a release over a short period of time, which is more consistent with an impact scenario. The orbit of this object is stable over many millions of years, but it has also been found to be a member of an extremely compact cluster of asteroids only about 1.5 million years old. It would appear that 331P and its fellow members of this young and compact cluster are the fragments of a major collision that took place about 1.5 million years ago. This may be, at least in part, responsible for its rapid rate of rotation.

Tidal Heating and Comet-like Behavior

Although not mentioned by Jewitt, one other cause of comet-like activity in certain objects might be worthy of a brief note. Picture a rather large object of cometary (that is to say, icy) composition orbiting a large planet, but also tidally influenced by a nearby massive moon of that planet. Such an object is caught in a tidal tug-of-war which, if sufficiently severe, may give rise to enough energy to turn the interior of the "cometary" body into a liquid—or at least, a slush—and drive comet-like activity. In our own Solar System, the Saturnian moon Enceladus exhibits a form of cryovolcanism which has been likened to cometary activity, triggered by internal heating generated by the tidal flexing resulting from Enceladus' 2:1 resonance with another Saturnian moon; Dione. A more extreme example of this process is experienced by that boiling, belching, cosmic Yellowstone Park that is Jupiter's innermost large Moon, Io. However, the activity of this excessively volcanic object goes beyond anything that could justifiably be termed "cometary"!

The Weird Geminid Parent

Gradually increasing in activity over the years, the December Geminid meteor shower is now one of the strongest of the year and is also well known for the number of bright meteors that it produces. Yet, for a long time, this shower presented a number of problems for meteor astronomers.

For one thing, there was no known comet associated with it. Other major showers could be associated with parent comets and it was believed that all meteor showers originated in comets, even if some of those objects had long since faded from view. The solution to the orphan nature of the Geminids was simply to assume that there had once been a comet associated with them but that it had faded and disappeared at some time in the past. Yet, the meteor shower's orbit was not typical of short-period comets. The period of a Geminid meteoroid is very short, just 1.7 years. Presumably, the parent body would have had a similar period of revolution, but it was not readily apparent how a comet could end up in an orbit of the Geminid type. Not, at least, during a length of time shorter than the expected lifetime of an active comet. What made matters even more difficult to understand was the very small perihelion distance of the order of 0.1 AU. If a comet did once inhabit that orbit, the powerful solar heating every 1.7 years or thereabouts would have quickly eroded away its store of volatiles.

Maybe the parent comet was one of unusual mass and dimension that could withstand such rugged treatment. There may even be some support for such a suggestion in the nature of the Geminid meteoroids themselves. These bodies behave as if they are relatively dense bodies and have a tensile strength greater than meteoroids associated with the majority of meteor showers. Maybe, according to one suggestion, the meteoroids of this shower originated deep within the core of a very large comet where they were formed under conditions of pressure, and even temperature, greater than that experienced by the average shower meteor. Indeed, looking at the properties of meteoroids from various well known showers, a sort of progression of tensile strength appears to emerge. At one extreme, we have the October Draconids associated with the short-period comet 21P/Giacobini-Zinner. These meteoroids are little more than dust bunnies, crumbing away into dust streaks high in Earth's atmosphere. The nucleus of this comet is apparently very loose and friable and it was suggested that it may be a relatively recent addition to the family of short-period comets, implying that the meteoroids constituting the Draconid shower have been derived from the surface layers of its nucleus. Although not specifically relating to the nature of the Draconid meteors, a study of this comet by Z. Sekanina concluded that its nucleus rotates very rapidly and likely has a broad but shallow shape. If he is right, it must look something like a spinning Frisbee! If it does have this form, no part of the nucleus is very far from the surface and no particles shed by this comet would have been subjected to more than a minimal degree of compaction.

Toward the other extreme are the Taurid meteors derived from 2P/Encke. These possess a far higher tensile strength and were presumably, according to this line of argument, once subjected to a significantly higher degree of pressure. That conclusion was thought to fit well with the nature of Encke. This object has long been thought of as the remnant of an initially very large comet and gives every indication of being a strong and probably quite dense object. Its frequent passages within the orbit of Mercury surely speak for its durability and its steady performance, free from events such as splits and outbursts, equally speaks of its stability.

Yet, "tougher" than even the Taurid meteoroids, the Geminids surely represent the opposite pole to the Draconids. The behavior of these meteoroids suggests a level of tensile strength consistent with their formation deep within the core of a very large cometary body. Unlike Comet Encke, this parent object had apparently broken up completely and vanished from the scene.

The above scenario more or less described the consensus of opinion at the beginning of the 1980s. Then, in 1983, the space-based infrared observatory *IRAS* discovered a new asteroid. This discovery was immediately noteworthy in two respects. First, it represented the first time that an asteroid had been discovered from a spacecraft and, secondly, the new asteroid (which was given the temporary designation of 1983 TB) was found to have a perihelion distance of just 0.14 AU, breaking the previous record of 0.19 hitherto held by 1566 Icarus. However, the biggest surprise came not long after the publication of the orbit of the new object when F. Whipple noted the very close resemblance of this orbit and that of the Geminid meteor stream. The parent body of the Geminids had at last been found! But what exactly was it? Was it a "genuine" asteroid or was it a comet that had lost its ability to produce a coma and tail?

The object—now better known by its permanent number and name, 3200 Phaethon—was closely observed for any sign of cometary activity, but none was found. Nevertheless, the clear association with a strong meteor shower and the lack of any other positive asteroid/meteor shower combination convinced most people that Phaethon had at one time been a comet, even it had now ceased to be active.

Not everybody was convinced however. The present writer and, independently, Rob McNaught of Siding Spring Observatory, privately and informally speculated that Phaethon might indeed be a genuine asteroid and that its severe heating around the time of perihelion may be causing its surface layers to crack and break up into dust and pebbles. Perhaps through rotation or some other means, this material could be shed into space, forming the Geminid meteoroid stream. Geologists are well aware of a phenomenon known as exfoliation affecting terrestrial rocks. Changes in temperature, expansion through heating and contraction upon cooling, weakens the surface layers of rocks, causing the outermost layer to detach as leaf-like flakes (hence the term "ex*foli*ation") and it seemed logical to suspect that something broadly similar might be happening on Phaethon as well, considering the temperature extremes to which this asteroid is frequently being exposed.

Another suggestion was that the Geminids were the product of a collision between Phaethon and another asteroidal body. As such an event is more likely to have occurred during the time around aphelion, the orbits of the Geminid meteoroids and the asteroid should converge near this point and be more dispersed closer to perihelion, if they are indeed the products of a collision. In fact, the opposite is the case, indicating that the particles were indeed shed close to perihelion and not near aphelion. Although it is not impossible that Phaethon sustained an impact near its perihelion, the chances of this having happened are small. The release of particles at that point in the asteroid's orbit is far more likely to have resulted from some form of heat driven process, either true cometary activity or something which mimicked it.

Continuing observations of Phaethon indicated that this object has a spectrum matching that of a B-Type asteroid, although there has been a degree of controversy concerning this identification. Assuming this classification to be correct, this does not make it a *very* good match with the several comet nuclei thus far observed, although it does at least place it within the range of dark objects. That of itself does not necessarily rule out a cometary origin however. We do not know how much diversity there may be amongst comet nuclei, nor can we be sure how the frequent periodic roasting that this object receives at perihelion may have affected the nature of its surface. Furthermore, all observations of comet nuclei have been of the surfaces of these bodies. But as we discussed earlier, a number of astronomers suggested that the Geminid meteors were formed at the core of a comet so large that a degree of differentiation had taken place. Whether any comets are differentiated, possessing solid rocky cores, was (and is) a contentious issue, but if some comets are differentiated and if one of these was the Geminid parent, then Phaethon may actually represent such a rocky core and not simply a comet nucleus that had either run out of volatile materials of had become so heavily encrusted that all activity had been smothered. If that is the true nature of this object, there is no reason to think that its reflectance spectrum would resemble that of (the surface of) a regular comet nucleus.

On the other hand, a B-Type spectrum matches Phaethon with one of the "big four" asteroids of the main belt: 2 Pallas. This is interesting, as Pallas is known to be associated with a family of B-Type asteroids, presumably resulting from an ancient collision between this object and another asteroid. It has also been found that asteroids of the Pallas family can dynamically evolve into Phaethon-type orbits, opening the very real possibility that this object is a child of Pallas and not a defunct comet.

The hypothesis of a Pallas association has gained rather wide support. It has also been established that Phaethon cannot be a dormant comet in the sense of one that retains ice shielded by an insulating blanket of non-volatile material. Its close passages of the Sun are too frequent for it to cool down sufficiently and, because of its small dimensions, even its very center maintains a temperature too high for ice to be stable. That finding does not, however, preclude it from being the core of a very large and differentiated comet nucleus, as one would not expect ice to be retained by such a body.

Nevertheless, Phaethon has now been found to be less than totally inert. It has been discovered to exhibit very weak and intermittent activity when close to perihelion. Images beamed back from the STEREO spacecraft in 2009 and 2012 revealed a brightening of the object and the appearance of a short dust tail. Oddly however, no such activity was evident in the intermediate return of 2010. On the returns in which a tail is evident, it is clearly comprised of fine dust and grows rapidly, reaching its full length of 250,000 km (150,000 miles) in a single day.

Although not driven by sublimating ice, Phaethon is, in the words of David Jewitt and Jing Li, a "rock comet". Asteroids of the B-Type are believed to contain hydrated materials and the high temperatures experienced by Phaethon are thought to cause desiccation and cracking of its surface, rather like the dried mud on a waterless lake bed. Fine dust released by this process is driven away by solar radiation pressure to form the tail. The activity of Phaethon, it would seem, is driven by number five and six in Jewitt's list of the possible causes of activity in some asteroids. There may even be some input from the third suggested process, electrostatic levitation of dust particles. Some of the dust generated by the cracking of surface material may be subject to this effect in a manner similar to what has been observed on the Moon, except that in the far weaker gravity of Phaethon, to say nothing of the stronger solar radiation at its perihelion distance, this dust would be whisked away into the tail rather than settling back onto the surface as the electrostatic effect waned.

Nevertheless, the fine dust forming the tails in 2009 and 2012 could not give rise to Geminid meteors. The particles that constitute this stream are simply too large to have been wafted skyward from Phaethon's surface in the manner described here. Something more dramatic must have occurred in the relatively recent past—some kind of outburst perhaps, maybe involving the breaking away of a large portion of material—to have given rise to the meteor shower which we see today.

It is interesting to note that B-Type asteroids, principally Pallas itself—have been named as the possible parent bodies of a rare type of carbonaceous chondritic meteorite known as CR2 meteorites. These are closely related to the more common (albeit still quite rare) CM2 meteorites such as the Murray, Murchison and Sutters's Mill. Only a small number of CR2 meteorites are known and most of these were "finds" (that is to say, meteorites that were not seen to fall and for which the fall date is unknown) in Antarctica and desert regions. Only three were seen to fall, if we include the Al Rais meteorite of 1957. Although included as a CR2 when this class was first recognized as separate from CM2, the Al Rais is anomalous and some meteorite experts argue that it should be placed in a category of its own, closely related to the CR2 meteorites but still distinguished from them. Be that as it may, two of the three "falls" that at one time were placed within the CR2 class—namely, Al Rais and Kaidun of 1980—fell while the Geminids were active, although neither meteorite arrived at the time of the shower's maximum. Given that Phaethon is likely to be related to Pallas and given that the Geminids are relatively slow meteors having velocities around the upper limit for larger objects to survive as meteorites, the intriguing possibility is raised that the arrival of two of these three meteorites while fragments of Phaethon were entering our atmosphere may not be simple coincidence!

Unfortunately, details of the fall of Al Rais have not been forthcoming, so it has not been possible to ascertain whether the time of day and trajectory of the fireball were consistent with a Geminid origin. On the other hand, the fall of the Kaidun meteorite in Yemen on December 3, 1980 was observed by a Soviet soldier at a base in South Yemen (which at that time was officially known as the Peoples' Democratic Republic of Yemen). Soldiers from the Soviet Union were stationed there at the request of the Marxist-Leninist government then in power in that region. The fireball was a daylight object, arriving in the morning at a time when the Geminid radiant would have been low in the sky in a west-northwest direction. According to the soldier's account, the fireball travelled from the northwest toward the southeast. The direction indicated is broadly consistent with a Geminid association. The witness may not have been very precise in his description of the direction and, because the body was significantly larger than the average Geminid meteoroid, it may not have followed the exact path of the majority of these objects and its radiant may therefore have been somewhat displaced from that of the main shower. Larger bodies would be less affected by the Yarkovsky effect, for instance. In short, the description of the trajectory of the fireball, in addition to the date and time of day of the meteorite's arrival, appear to be consistent with a Geminid connection. At the very least, there is nothing obviously *inconsistent* with this object having been a Geminid!

It is also interesting to note that, although the bulk material of the Kaidun meteorite was of the CR2 class, it possessed a large number and wide variety of inclusions of different meteorite types. As one author phrased it, the meteorite contained "everything but the kitchen sink"! If it did come from Phaethon, and originally from Pallas, these bodies might be a lot more complex than they superficially appear to be.

The other member of this meteorite trio—actually the first CR2 to have been observed to fall—is the Renazzo meteorite. This object fell on January 15, 1824 and is now regarded as the prototype of the CR2 class. It is the "R" in "CR2". The date of its fall lies outside the dates of the Geminid shower's activity and, moreover, there is no clear evidence that the Geminids even occurred at the time the meteorite fell. Although there are records of meteors seen in the early 1800s that may have been Geminids, clear evidence of the shower's existence is not present until the second half of the nineteenth century. Even then, the shower was a lot less active than it has been in recent years. Earth's encounter with this meteoroid stream has not been of very long duration and there will come a time when, once again, our planet will cease to traverse the stream and the Geminid meteor shower will be consigned to history.

Nevertheless, it may be possible that the Renazzo meteorite was associated with another known asteroid. On January 7, 2002, the small asteroid designated 2001 YB5 passed a mere 0.0056 AU of Earth. A watch was kept for a possible meteor shower predicted for around 12 h UT on that day and meteor observers were not disappointed. Several stations reported observing a minor, but quite definite, shower of meteors radiating from the predicted region near the edge of the constellation of Cancer at around the predicted time. Furthermore, 10 days later, a brilliant fireball was observed from The Netherlands as well as from parts of Germany and a sufficient number of observations were obtained to indicate a radiant within Cancer, although it could not be decided whether the radiant coincided with that of the 2001 YB5 meteors or whether the fireball was associated with the annual Delta Cancrid shower. This shower is known to produce the occasional fireball and (as we shall see in due course) seems to have been responsible for the brilliant one seen over the Baltic Sea on January 17, 2009 and which deposited a tiny meteorite just outside Maribo in Denmark.

Actually, 2001 YB5 has been named as one of the possible parent bodies of the Delta Cancrids, at least, of the southern branch of this ecliptic shower. As we shall later see however, its orbit is not strikingly close to that of this meteor stream and there are some more promising candidates—but more about that later!

What is more interesting in the present context is that this asteroid appears to be of the B-Type, according to the results of an analysis B. Yang and colleagues. Is it possible that it is the parent object of the Renazzo meteorite? Alas, the details of the fall of this body are too vague to be sure, but apparently the meteorite arrived in the evening (nevertheless, from what direction we do not know) which at least is not inconsistent with a radiant in Cancer.

The Mysterious 322P/SOHO

Examining images from the LASCO C3 coronagraph on board the SOHO space-based solar observatory on September 5, 1999, Australian amateur astronomer Terry Lovejoy (now better known as the discoverer of six comets that bear his name, most notably the great Kreutz sungrazer of 2011) could scarcely believe what he was seeing. Recounting the experience some time later, he jokingly remarked that he thought he was seeing something that should not be observed! Clearly visible in the LASCO images, was an object of star-like appearance that appeared to be looping around as it approached the Sun. It seemed to move in, then reversed briefly, before continuing its path toward the Sun!

The object was not an alien spaceship (of course, Lovejoy never believed that it was!) but it did turn out to be something almost as weird. Although it appeared to be asteroidal, its brightness (at around magnitude six) would have implied a diameter—had it been a bare asteroid—in the order of 10 km. Had there been a body of that size looping around in the midst of the inner planets, it would surely have been found long ago. Presumably therefore, the new object was a comet with a very small and condensed coma, indistinguishable from an asteroid on the scale of the LASCO 3 images. The strange "looping" orbit was not as weird as it looked. The apparent reversal was simply due to the changing relative positions of the Earth and comet. A preliminary parabolic orbit revealed that the comet passed the Sun at just 0.056 AU but, unlike the Kreutz objects that had constituted most SOHO discoveries at that time, this body survived and was observed before and after its solar close encounter.

September 2003 saw a comet follow the same track and, thanks to orbital computations by S. Honig, this was shown to be, not a second object belonging to the same group, but an actual return of the 1999 object. Honig then predicted the comet's next return in 2007. The comet was indeed observed on schedule and Honig's predicted time of perihelion passage turned out to be accurate to within an hour. The comet, which has been given a periodic comet number and officially designated 322P/SOHO (despite one suggestion that it should have been named "Honig" in the Halley-Encke tradition), has since returned in 2011 and 2015.

A comet moving in a similar orbit was, however, found in LASCO images in 2002. This one, designated as C/2002 R5 (SOHO) has a somewhat longer period and next returned in 2008, when it was given the designation C/2008 L6 (SOHO). It is interesting to note that, at the 2008 return, this object was preceded by a second comet—a small companion fragment of the larger one—travelling in the same orbit but arriving at perihelion just 18 min before 2008 L6. Because this second object was actually found after the principal object, it has been given the designation of 2008 L7 (SOHO). Presumably, the parent body—C/2002 R5 = C/2008 L6—had split away from 322P several revolutions earlier, but examination of LASCO images at the time of its calculated prior return in November 1996 failed to reveal it. That may be an important (non-)observation about which more will be said later. Be that as it may, the two comets of 2008 plus 322P constitute what is known as the Kracht-2 comet group, named in honor of R. Kracht who first drew attention to the orbital similarities between its members.

The mystery of 322P concerns how a small comet can pass so close to the Sun every four years and still remain active. This is where the story takes an interesting turn. As the comet approached its 2015 perihelion passage, observations were possible from Earth and the results published by Matthew Knight and colleagues in *The Astrophysical Journal Letters* for April 23, 2016. They make intriguing reading.

The comet was observed from 2015 May 22 through to July 24 of that same year; the earlier observations being made with the Very Large Telescope and the Lowell Observatory Discovery Channel Telescope and the later ones with the Spitzer Space Telescope. Throughout the period of observation, the comet appeared as a very faint asteroidal body revealing no hint of activity. Depending upon the object's albedo, its diameter is somewhere between 150 and 320 m, according to Knight and his team. These researchers also found that the comet was rotating at an unusually high velocity, completing one full revolution in just 2.8 (plus or minus

0.3) h. For such a fast spinning body to hold together, its density must be around 1000 kg per cubic meter, higher than that derived for any other comet but more in line with what is expected for a rocky asteroid. The reflectance spectrum obtained for this body also appeared to be more typical of asteroids than comets, being rather similar to asteroids of the V or Q types. The first of these have reflectance spectra matching that of Vesta and agree closely with the spectra of basaltic achondrite HED meteorites, which are thought to derive from asteroids of this type. Bodies of the Q type seem to match the composition of ordinary chondrites meteorites.

On the other hand, the dimensions of this object as derived by Knight et al. underscored the earlier conclusion that 322P was certainly active at each of its observed perihelion passages. A brightness prediction for around the time of perihelion based upon the absolute magnitude of the bare nucleus as derived from the observations of Knight's team, and assuming simple reflection of sunlight from an inert body, yields a maximum computed brightness around eight magnitudes, that is to say some 1700 times, fainter than the brightness actually achieved by this object as estimated from the LASCO images! It is interesting to note however, that this difference in brightness is in the same ballpark as that between the bare nucleus and the total coma of an average active comet.

We seem to be confronted with a real puzzle here. On the one hand we have an object that acts like a typical comet when near perihelion and from this we may be encouraged to conclude that its activity is driven by sublimating ice. And yet … this object is small. Having a higher albedo than other observed comets, its diameter is probably toward the lower end of the range given above, but even assuming something of the order of the upper end of the range—300 m for instance—it is unlikely that ice would be stable even deep below the surface of this body. With a perihelion distance of just 0.05 AU from the Sun and a period of only 3.99 years, this body receives a severe roasting on a regular short-term time scale and it is unlikely that even its core is cool enough for ice to persist. Surface temperatures reach over 1000° every 4 years and this heat penetrates downward, warming the underlying rock to the very center.

One might suggest that the activity of this object is similar to that of Phaethon, that is to say, that it develops a coma of small dust particles released from the rocky surface through exfoliation caused by the expansion and contraction of rocks containing hydrated minerals as they are alternately heated and cooled while the object rapidly rotates. The problem with this idea, however, is that the brightness of a dust coma of this sort should be strongly enhanced at large phase angles. In 1999 for instance, the comet briefly reached large phase angles about 12 h before perihelion. If the coma was composed of dust, there should have been a sharp spike in the light curve; however nothing of the sort appears to have happened. The coma is apparently composed of gas, though apparently not arising from the sublimation of ices.

Temperatures close to perihelion are so high that small particles of what would be considered "rocky" material would probably evaporate. Research has shown that silicates begin to evaporate at similar temperatures and the appearance of a tail of neutral iron atoms associated with C/2006 P1 (McNaught), otherwise known as the Great Daylight Comet of January 2007, is thought to have indicated the evaporation of fluffy grains of troilite (FeS), a mineral that has been found in meteorites. This comet had a perihelion distance of 0.17 AU, so did not reach the levels of temperature encountered by 322P although it certainly experienced a torrid time when close to perihelion.

Because of the difficulties posed by identifying this object as a "classical" comet, Knight suggests that 322P is really an asteroid that has over the course of many centuries been gravitationally perturbed from the main belt into its present sunskirting orbit. That would avoid the difficulties already mentioned, albeit only at the price of raising another, namely, the problem of explaining why this appears to be the only sunskirting asteroid that becomes active at perihelion. Other sunskirting asteroids are known (though not with perihelia as small as 322P) and there must surely be others that do come as close, or even closer, to the Sun than 322P. As small objects, they are very difficult to discover unless they become active near the Sun … which is the whole point of the problem! If others *do* become active, some at least *should* have been found!

Knight suggests that a clue to the activity of 322P may be found in the existence of other members of the Kracht 2 comet group. Maybe the splitting away of these other objects has exposed interior materials that are more vulnerable to the Sun's heat than the surface of the asteroid/comet. He is not suggesting that there is ice within the body of this object, but maybe the material there is more crumbly than the thoroughly heat annealed surface may be.

There is some support for this idea in the behavior, as well as in the mere existence, of the other members of this comet group. The first of the "secondary" members discovered was designated as C/2002 R5 (SOHO). It was initially thought to be moving along a parabolic orbit (322P had, at that time, only been observed in 1999 and was not yet known to be periodic) but was later linked with C/2008 L6 (SOHO) and 2008 L7 (SOHO). As already mentioned, the comet has a longer period than 322P and had apparently split during its 2002 return, subsequently coming back in the company of a fragment in the form of a companion comet.

Dynamical calculations by Z. Sekanina revealed that the comet had actually split some time between 2 and 10 months prior to its 2002 perihelion passage. Apparently, it was already double when observed in LASCO images that year, but the two portions of the split nucleus were encompassed within a single compact coma and their separation was well below that of the LASCO coronagraph. Continuing to separate, the two fragments returned as two comets in 2008. R. Kracht found that C/2002 R5 would have previously been at perihelion in November of 1996, at a time when SOHO was already operating, however a careful search of LASCO data for that time failed to reveal any trace of it. Presumably, prior to the 2002 split, it was either inactive or too weakly active to register in LASCO data. If that is the correct diagnosis however, it might also give a clue to the performance of 322P. That is to say, if the "child" needed to split before it could become active enough to be recorded in LASCO images, perhaps the "parent" also had to split to achieve the same result. If the fragment that was to become C/2002 R5, and ultimately C/2008 L6 and C/2008 L7, only activated sufficiently to be discovered after it split into two parts, maybe the parent object only activated after the 2002 R5 fragment broke away from it and exposed its deep interior.

That, in essence, is Knight's speculation and he furthermore suggests that this initial split may have resulted either from rotational spin-up or thermal stress. Maybe it was a combination of both factors.

If the underlying parts of 322P are more friable than the surface, the scar left after the fragment split away presumably allows solar heat to reach these less stable materials. Thermal stress may cause dust to be released and, if rapid rotation caused the split in the first place, this may also help throw off dust particles released by thermal processes. As suggested above, these particles may quickly evaporate to produce the gaseous coma. Solar radiation might also sputter atoms directly from the exposed rock and sweep them away from the nucleus. This is the process by which the planet Mercury is thought to sustain its tenuous exosphere. Dust created by the thermal cracking of loose rock may also be elevated via electrostatic repulsion, before being swept away by solar radiation and evaporated by the intense heat of the nearby Sun.

As a wild suggestion, we might wonder if florescent or thermo luminescent materials may be present in the released dust (or even at the surface of the body) and whether these could contribute to some of the emitted light. Realistically though, if this process is present at all, it is likely to be a very minor contributor at best.

A further complicating factor was added to the mix when the other members of the Kracht 2 comet group, C/2008 L6 and L7, returned to perihelion in 2014 and were again active and recovered in LASCO data. The main comet of this pair (C/2008 L6 = C/2002 R5) was found by Zhijian Xu on 2014 March 7, a full week ahead of expectation! The small comet, C/2008 L7, was then trailing by 2.6 h. Reiner Kracht was able to link the 2014 positions with those of the earlier returns, however non-gravitational effects were evident in the motion of each of these comets. These effects are usually associated with sublimating ice, but presumably in this instance they were being caused by the ejection of material by other means. Their presence, however, hints that *something* is behaving *like* sublimating material and driving a form of activity which closely mimics that of "classical" comets!

Whatever the truth may be concerning this object, its discovery has certainly challenged our ideas as to the nature of what may or may not be given the description of "comet"!

Comets Behaving Like Asteroids

The Mysterious 107P/Wilson-Harrington

One of the strangest comets yet discovered had its image first captured on photographic plates for the Palomar Observatory Sky Survey on just three nights back in November 1949. The first image, secured on November 19, was found by A. Wilson and R. Harrington and appeared clearly cometary. Admittedly, no extended coma was detected, but a straight tail was evident, especially on the blue-light plate (two plates were obtained on each night of the Survey, one on a blue-sensitive and the other on a red-sensitive photographic plate). The tail was still evident of the red-light photograph, but only weakly recorded. Strangely, the images secured on the nights of the 22 and 24 of November, both in blue and in red light, revealed a totally asteroidal image, devoid of any suggestion of either coma or tail. The comet was passing rather close to Earth at the time of discovery and with positions available for only three nights covering a small arc of its track across the sky (which, because of its relative proximity to Earth, only represented a very small section of its solar orbit) only a very rough orbital computation could be made. A short-period ellipse was hinted at, maybe with a period as short 2.31 years according to one estimate, but it was so uncertain that only a parabola was given in most catalogs of comet orbits.

There the situation rested until November 15, 1979, when Eleanor Helin of Palomar Observatory discovered a near-Earth asteroid following a path that looked more like the orbit of a short-period comet than that of a regular asteroid. Nevertheless, the orbit was rather more stable than that followed by the average comet and the object—designated as 1979 VA—revealed no apparent sign of cometary activity. Having a period of just 4.29 years, the object was recovered on December 20, 1988 and was given the permanent asteroid number of 2015. At that point, B. G. Marsden and others noted that the orbit of this asteroid bore some resemblance to that of the comet Wilson-Harrington of 1949 and the identity of these objects was confirmed in 1992 when E. Bowell of Lowell Observatory, during a search for earlier images of 2015, found that it did indeed coincide with the 1949 comet. Following this identification, the object was classified both as a comet and as a minor planet; 2015 Wilson-Harrington = 107P/Wilson-Harrington.

The comet has been regularly observed at recent returns and quite a deal has been learned about it. In terms of its reflectance spectrum, it is broadly speaking a C-Type body with a rather flat spectrum (FC) and from observations of variations in the brightness of the object, D. Osip et al. (*Icarus*, 114, 423–6, 1995) derived a rotation period of 6.1 h (plus or minus 0.05 h). This period has been effectively confirmed more recently by I. Ferrin et al. This makes Wilson-Harrington a member of the fast-rotator class of small objects. Ferrin notes that the rotational light-curve is rather odd in having a very sharp "saw tooth" profile in his data plot. From this he deduces that Wilson-Harrington must have an odd shape—with sharp edges! Perhaps this says something about the early fragmentation history of this body.

The biggest mystery however, is why this strange object is only known to have displayed a tail on one night in 1949 but has maintained a completely asteroidal appearance on every observed return since.

One suggestion is that it was impacted by a meteorite in 1949. It is not suggested that it is an inert body from which an impacting meteorite raised a cloud of dust, as that does not fit the observations. What is suggested is that Wilson-Harrington was once an active comet that has built up a thick insulating layer during the course of many perihelion passages but which nevertheless still contains a store of ice buried beneath this refractory blanket. It is suggested that a meteorite striking this surface layer may have dislodged a small section of the insulating blanket and permitted sunlight to briefly reach some of the underlying ice, triggering a short outburst of activity.

Although that idea intuitively seems plausible, it does have its difficulties. In common with the alternative idea that a meteorite striking a non-cometary asteroid caused the 1949 tail, the meteor-strike outburst scenario also implies that the solid body should become surrounded by a "coma" of dust and/or gas and that the total brightness of Wilson-Harrington should have increased at the time. However, Ferrin's investigations concerning the brightness of this object finds no evidence that it was any brighter in

1949 than it was at the corresponding place in its orbit at any of the "inactive" returns observed in more recent years.

The only difference seems to be the transitory appearance of a tail in 1949. But was this tail composed of dust or of ionized gas? The rather unstructured appearance might suggest dust, but the fact that it showed up a lot more clearly in the blue images than it did in the red might be taken as evidence for gas. The greater clarity on blue images may not, by itself, imply a gas tail however. Ferrin refers to a statement by R. West to the effect that dust tails have not infrequently shown more clearly in blue-sensitive photographic images due to the different emulsions employed in the red images. Both West and Ferrin favor a dust tail in 1949. On the other hand, Y. Fernandez et al. (*Icarus*, 128, July 1997) argue for a plasma tail comprised of CO^+ and H_2O^+ ions. They trace the trajectories of hypothetical dust particles emitted by the comet and find that these would not have produced the observed tail unless they were very large. Particles of the required size would not, however, have appeared brighter in the blue-sensitive image and the tail itself would have been longer lasting than the one actually observed. D. Jewitt likewise remarked that the orientation of the tail was not consistent with dust. On balance therefore, it seems that a plasma tail is probably the more likely explanation for the observed phenomenon (Fig. 2.5).

If we assume that the tail was plasma, the mystery of its brief duration might be explained in terms of a type of phenomenon sometimes witnessed in association with the plasma tails of comets, about which more will be said later in this book. These events, "tail flares" as we may term them, are typically very brief and are accompanied by only slight enhancement of the comet's total brightness. They seem to be triggered by solar events rather than by processes intrinsic to the comet itself. In the Wilson-Harrington instance, the virtual lack of any coma would imply that any total enhancement that might have occurred would have been too slight even to register.

Whatever the truth concerning the 1949 tail, the popular idea is that its appearance that year and apparent lack of any evidence of activity in the more recent observed returns indicates that the comet was on its "last gasp" in 1949 and has since become extinct or, at best, completely dormant. Maybe, as already remarked, this

FIGURE 2.5 Enhanced image of Comet 107P/Wilson-Harrington in 1949 clearly revealing the presence of a tail. Credit: ESO/Palomar Observatory

last gasp was brought about by a meteorite impact, although as we have also remarked, that scenario encounters difficulties concerning the appearance of the comet at the time. If the impact idea has to be abandoned though, it is an uncomfortable (although admittedly not impossible) coincidence that, after presumably thousands of years, this comet gave up the ghost just as observational technology reached the point where the event could be recorded by terrestrial astronomers!

Ferrin takes a somewhat different view. Noting work by G. Herman and P. Weissman, in 1987, concerning the propagation of a thermal wave through cometary material, he points out that at a distance of 1 AU from the Sun (roughly that of the perihelion distance of Wilson-Harrington) solar heating can only penetrate to a distance of 250 m below the surface of a cometary nucleus. For a comet to be truly extinct—that is to say, utterly devoid of volatile material and therefore incapable of producing any further activity—it can be no larger than 500 m in diameter if the distance of its perihelion is equal to that of Wilson-Harrington. For periodic comets having larger perihelia, the maximum size would be even less although truly extinct comets having larger dimensions can exist in Encke-like orbits where far greater temperatures are encountered during the perihelion section of their orbits. The diameter of Wilson-Harrington has been determined as just over three kilometers, implying that much of its interior has not experienced solar heating and a good supply of ice and other volatile material should still be present.

According to Ferrin, comets can fade out either by totally dissipating (in the case of fragile and very icy ones), exhausting their volatiles but persisting as inert objects (extinct comets—all of them being small objects for the reason just discussed) and "suffocated" comets, that is to say, comets that have built up such a degree of insulating crust as to totally screen their underlying ice from the Sun's heat. Unlike suffocated human beings however, these comets are not dead. They are simply comatose. Enough ice remains within these dormant comets to rejuvenate them into active objects if for some reason the suffocating, insulating, layer of non-volatile material is disrupted or peeled away. This may happen if the comet is struck by a meteorite, especially if the impacting object is large enough to split the comet apart and thereby expose large quantities of internal ice. Another cause of splitting and rejuvenation might be a very close approach to a planet. Yet another potential cause is rotational instability, in the manner already discussed in relation to some active asteroids.

It is also possible that, although a comet has been dormant for many returns in the sense that no material has escaped from it to form a coma or tail, the insulating layer has been thin enough to permit sufficient solar heating of the underlying ices to create pockets of trapped gas, building up around the time of perihelion and re-freezing again as the comet recedes from the Sun. We might imagine a situation where this repeated buildup of gas progressively weakens the insulating layer until the resulting stress eventually proves too much and a section is blown away, in the process releasing a fountain of gas and dust. If an eruption of this kind is sufficiently powerful, the nucleus itself might be broken into several pieces and much of the comet's internal ice exposed. This could account for the major outbursts and splitting of comets such as, for instance, 73P/Schwassmann-Wachmann in 1995.

Another way that a dormant comet might be rejuvenated is through gravitational perturbations of a major planet (Jupiter being the usual chief culprit in this drama) deflecting it into an orbit having a smaller perihelion distance. This situation may even trigger the abovementioned explosive scenario; although it could just as easily result in a relatively gentle activation of the comet as increased solar heating penetrates down to what had previously been undisturbed ice.

Ferrin argues that the latter process is the one most relevant to the instance of Wilson-Harrington. Contrary to the popular model of this comet having recently been active and having gone dormant only during the last 60 years or thereabouts, he argues that it passed into a dormant phase far earlier and that during the past century it has actually regained a slight degree of activity. In support of this, he presents observational evidence that he interprets as a sign of continuing weak activity, not just in 1949 but also during the returns of 1979, 1992, 2005 and 2009. By carefully plotting the most accurate magnitude estimates derived from several sources, he found that the object's intrinsic brightness shows a small but persistent excess during the time period beginning about 26 days after perihelion and extending to around 55 days after. This also covers the period during which the tail activity was noted in 1949. The excess brightness only amounts to about 0.5 magnitudes greater than that predicted on the assumption that Wilson-Harrington is totally inert and merely reflects the Sun's light, but it is too persistent to easily dismiss and does not appear explicable in terms of phase effect, difference in albedo or the like. According to Ferrin, the thermal wave resulting from solar heating of the surface material during perihelion passage has travelled sufficiently deeply by the time the brightness excess becomes apparent to have reached subsurface ice. Gas from sublimating ices, and maybe small dust particles as well, can be thought of as seeping up through the surface crust and forming something like a gently glowing ground fog spread across the surface of the object; although calling this diffuse mantle a "fog" is certainly a gross exaggeration. Even calling it a "haze" is too strong term, as the fluorescing gas is insufficient to be detected from Earth as a coma or even to "soften" the comet's image, which has always remained sharp and asteroidal throughout. Nevertheless, it is enough to add a detectable contribution to the total brightness of the comet.

Ferrin finds possible support for activity in a couple of other observations as well. For instance, a spectrum secured by M. Ishiguro and colleagues in 2009, appeared to show a slight brightness enhancement in the region where three C_2 emission bands appear in the spectra of typical gaseous comas. Although Ishiguro concluded that the comet was not active, Ferrin draws attention to the fact that this spectrum was taken 55 days after perihelion, toward the end of the period in which he argues that activity is present, and that the slight enhancement in brightness in that region may betray the presence of C_2 emission close to the surface of Wilson-Harrington.

A second possible indication of activity is suggested by the difficulty encountered by S. Urakawa et al. in determining the comet's rotation period during a time span from 44 to 59 days following perihelion. Noting that this also covered the active period, Ferrin explains the apparent obscuration of the rotation light-curve as being due to the presence of a very small coma at that time. Light from gaseous emission, and maybe even reflection and scattering by the presence of fine dust, may have sufficiently contaminated the reflected light from the surface of the body itself to mask the small fluctuations due to the latter's rotation.

The slow reduction in the comet's perihelion distance, that orbital calculations have shown to have taken place since 1928, has, Ferrin argues, resulted in the previously dormant comet waking from what may have been a long slumber. It has, however, only awakened to a somnambulistic state rather than to full vigor and because there is no dramatic reduction in its perihelion distance looming in the foreseeable future, it will likely go back to its slumbers as the supply of ice touched by the thermal wave gradually becomes exhausted.

If Ferrin is correct in his assessment, it may also be true that the comet continues to develop a very faint (sub-visual) tail and, if our suggestion that the tail event photographed in 1949 constituted a plasma-tail flare, it seems entirely possible that similar events may still occur. In fact, given the brief duration of these tail events, it is likely that more *have* taken place in the years since 1949 but have simply gone unobserved. If similar events taking place in bright comets such as 1978 T1, 1982 M1 and 2007 F1 could have been so poorly witnessed (as we shall see in due course), it would not be at all surprising if Wilson-Harrington has experienced unobserved tail flares. Because these occurrences are of such brief duration, the window of observability is narrow and there is certainly no guarantee that it will open over the dome of an observatory where the scheduled imaging of Wilson-Harrington forms part of the night's observing program! For that reason alone, this object should be monitored as frequently as possible at future apparitions. An opportunity for well equipped amateur astronomers is surely presented here.

The orbit of Wilson-Harrington passes close to Earth, so if this comet was once sufficiently active to shed relatively coarse dust particles, it would be a good candidate for being the parent object of a meteor shower. Indeed, J. Drummond (*Icarus*, 146, 2000) gives two theoretical radiants for possible Wilson-Harrington meteors; on September 8 (at RA = 18 h 41 m, Dec. = –24° 48′) and on October 2 (at RA = 17 h 24 m, Dec. = –21° 42′). Given the very low activity of the comet today and the likelihood that the present meager level was preceded by an extended period of complete dormancy, it is likely that any meteors associated with this comet have been well scattered from their original orbit and that the true radiant is now very diffuse. Any activity that may occur is likely scattered throughout September from a very broad region of sky. Moreover, any meteors from this source encounter Earth at very low velocities, so they would be fainter than correspondingly-sized particles entering our atmosphere at velocities more representative of typical cometary meteor showers. On the other hand, given the presumed age of any meteor stream associated with this object, most of the small particles have probably been swept out of the stream, so that what is left in Earth-encountering orbits are probably larger objects capable of producing fireballs. In short, a meteor stream associated with this comet might principally consist of bright slow-moving fireballs.

Examining lists of fireballs independently prepared by I. Halliday and R. E. McCrosky from Canadian and North American data between 1961 and 1984, Alexandra Terentjeva noted the presence of several apparent streams of fireballs. In her list published in 1989, one of the streams consisted of several fireballs observed on September 13 and with a radiant close to the region of the star Gamma Sagittarius. An average orbit was computed for the "September Gamma Sagittarids" of fireball stream number 40 and it has since been suggested that Wilson-Harrington might be the parent object of these meteors. The orbit of the comet and that derived by Terentjeva for the fireball stream are not, it must be said, convincingly close, however if the comet released these objects long ago a very close match with the present Wilson-Harrington orbit need not be expected. Nevertheless, the fireball orbit does display a far greater match with that of the asteroid 1989 VB.

There are several methods by which orbits of Solar System objects may be compared in order to find possible associations. In a paper published in the journal *Icarus* in 1981, J. D. Drummond put forward a version of the so-called *D discriminant* by means of which orbits may be compared according to the values of their perihelion distance, eccentricity, the angle between their orbital planes and the difference in their perihelion directions. If the orbits of two bodies, when compared according to the Drummond version of the D discriminant (denoted by D′) yields of value of D′ equal to or smaller than 0.105, the orbits are considered to be related. If we are dealing with objects pursuing more or less eccentric orbits within the inner Solar System, a small value of D′ probably means that these objects have relatively recently split away from a single body as the gravitational perturbations of the major planets cause orbits to drift apart over periods of a few tens of thousands of years or less. A small D′ value might, alternatively, imply that the objects in question have followed parallel dynamical evolution, although in cases where orbits are rather atypical the assumption of a common origin is probably the best option.

Comparing Terentjeva's fireball orbit and that of 1989 VB yields a D′ value of just 0.03, implying a strong relationship between these orbits.

This asteroid can make close approaches to Earth and a theoretical meteor radiant for particles associated with it was derived, by Drummond, for October 6 at RA = 17 h 50 m, Dec. = −34° 6′. Its meteors would be even slower than those from Wilson-Harrington.

About 1990, Australian observer Paul Camilleri was watching for possible meteors associated with Wilson-Harrington when he noted a couple of possible candidates (albeit not necessarily on the same night) in addition to a meteor that had such a slow motion as to have been initially mistaken for an artificial satellite. This trajectory of this meteor appeared consistent with it having come from the 1989 VB radiant and, in contrast to those which may have been associated with Wilson-Harrington, it showed no signs of fragmentation. Interestingly, the 1989 VB radiant does not lie very far from that estimated for the Murchison meteorite of September 28, 1969, although that may be pure coincidence. We will say more about 1989 VB and its possible meteors in a little while.

Returning, for the moment, to Wilson-Harrington, a more likely associated fireball was the one observed from the region of the town of Allan in Saskatchewan on October 19, 1979. This object is listed as Number 498 in the list of unrecovered Canadian meteorites compiled by I. Halliday et al. from photographs by the Canadian fireball network between the years 1971 and 1985. This very slow, fragmenting, fireball possessed all the hallmarks of a potential meteorite. Moreover, Halliday noted that its strong tendency to fragmentation marked it out as the best candidate for being a carbonaceous chondrite amongst all the objects in his list. Unfortunately, thanks in part to the hilly terrain in which any of its fragments may have fallen, nothing was ever recovered. The trajectory of this fireball, however, indicated a radiant very close to that calculated for Wilson-Harrington meteors and its computed orbit, when compared with that of Wilson-Harrington, yielded a D′ value of 0.087. Moreover, the date on which it fell was just 10 days prior to Wilson-Harrington passing only 0.091 AU from Earth. Nothing of this was known at the time however, as the comet was not rediscovered (as "asteroid" 1979 VA) until November 15. However, in 1988 H. Campins and T.Swindle singled out this fireball as representing a very strong candidate for being a fragment of Wilson-Harrington.

A search through Halliday's unrecovered meteorite list also revealed three possible members of the Gamma Sagittarid fireball stream. Interestingly, these meteors contrasted with number 498 (and with the Murchison meteorite, for that matter) in showing only a minimal tendency to fragment, in this respect resembling Camilleri's "slow" meteor and indicating a relatively high tensile strength—higher, at least, than that displayed by carbonaceous chondrites of the lower petrologic types. The three fireballs in question were number 189 (September 14, 1975), number 884 (August 29, 1983) and number 886 (September 7, 1983). The last of these gave the closest D′ comparisons with both the Gamma Sagittarids and 1989 VB (D′ = 0.07 and 0.05 respectively). Of the other two, 189 yielded D′ values of 0.1157 with the fireball stream and 0.0915 with the asteroid, whereas 884 gave 0.0897 with the Gamma Sagittarid fireballs and 0.1164 with the asteroid. Comparing the orbits of the three meteors themselves gave D′ values of 0.1504 between 886 and 884, 0.0618 (886 and 189) and 0.2021 (884 and 189). It seems likely that there is weak activity, associated with 1989 VB, from late August through into October and that the fireballs of September 13 form part of this. Coincident with this, activity from Wilson-Harrington may also persist throughout this period. Both objects apparently produce fireballs, but if we are correct in our assessment, the parentage of the different fireballs is distinguishable according to their tendency toward fragmentation, with the Wilson-Harrington objects being the more friable.

Which brings us to the Murchison meteorite. This object seems to have had a radiant very near that expected for meteors from Comet Finlay and the present writer has suggested a Finlay origin in the past.

Nevertheless, Wilson-Harrington also looks promising. In fact, when all is considered, it could be argued that it emerges as the better candidate. In a paper published in the International Meteor Organization journal *WGN* for August 2011, Terentjeva and S. Barabanov suggest that Murchison and Wilson-Harrington probably shared the same orbit in the past. Moreover, the D′ value for Wilson-Harrington and the Murchison orbit given by these authors (averaged from several rather close possible orbits derived for the meteorite) is just 0.0296. This Murchison orbit also gives a D′ value of 0.084 with fireball 498, but what turns out to be even more striking are the comparisons between the latitude and longitude of perihelion of the orbits of Wilson-Harrington, Murchison and fireball 498.

Comparing the latitudes and longitudes of perihelion (denoted as B and L respectively) of the orbits of Solar System bodies is another way of determining whether the objects following those orbits may be physically related and, perhaps, share a common origin. If these values differ by just a few degrees, association is probable. Latitude and longitude of perihelion may be calculated as follows:

$$B = \arcsin(\sin i \times \sin\omega)$$

$$L = \Omega + \arctan(\cos i \times \tan\omega) \quad \textit{or}$$

$$L = \omega + \Omega$$

Where i is the inclination of orbit, ω denotes the argument of perihelion (i.e. the angle from the ascending node, or point where the object's orbit intersects the plane of the ecliptic as the object moves northward, to the object's perihelion, measured in the plane of the ecliptic) and Ω is the longitude of the ascending node (i.e. the angle from the first point of Aries to the ascending node measured in the plane of the ecliptic).

These values for Wilson-Harrington, Murchison and fireball 498 are as shown in Table 2.1. Orbits revealing differences of only

Table 2.1 Comparison of Latitudes and Longitudes of Perihelion of the Orbits of Wilson-Harrington, Murchison Meteorite and "Canadian" Fireball 498

Wilson-Harrington	Murchison	Fireball 498
L = 1.95	L = 3.2	L = 3
B = 2.76	B = −0.07	B = 0.7

a few degrees in their latitudes and longitudes of perihelion are considered to be related and the objects following these orbits have a good chance of sharing a common origin.

It is a pity that no fragments of fireball 498 were recovered as it would have been interesting indeed to compare these with the Murchison meteorite. Alas, the chances of finding any fragments that may have fallen from the fireball are now essentially zero, although it is well to remember that if one (or two?) meteorites have fallen from Wilson-Harrington debris during the past 50 years, there is a reasonable chance that another will come along in the not-too-distant future and, given the coverage of the sky from the number of photographic stations now in operation, there is also a reasonable chance of recovery if one should land in a region covered by these photographic patrols.

Wilson-Harrington, as we have seen, was first listed as a comet, then as an asteroid and finally as both classes of object. In that respect, it exemplifies more than any other known body the merging of these two classes of minor Solar System body. The 1949 tail image was, however, somewhat fortuitous. Whether it was a tail flare as suggested here or whether it had some other origin, its visibility appears to have been short lived and could easily have been missed. Had that happened, the object would have been listed as an asteroid to this very day, although, no doubt, with continuing speculation as to whether it might be a dormant comet. One thing for sure, its name would not be the very cometary appellation of "Wilson-Harrington"!

"Ghost Comets"?

Something not unlike this hypothetical alternative actually happened with respect to another rather similar object. On September 26, 1983, Paul Wild at the Zimmerwald Observatory discovered an asteroidal body that was soon given the provisional designation of 1983 SA. Further observation subsequently enabled an orbit to be computed and the object was found to be moving in a rather eccentric (eccentricity computed at 0.71) elliptical orbit having a period of 8.76 years. With perihelion at 1.23 AU, the asteroid did not venture within the orbit of the Earth and was therefore not of the Apollo class, although it did come within that of Mars and was listed as an Amor. Very close approaches to Earth were not possible, although it could venture as close as 0.3 AU of our planet.

In time, the orbit was established with greater precision and further passages of the asteroid observed, enabling it to receive the permanent designation of 3552, as well as the name of Don Quixote. Certain physical properties of the object were also determined. For a start, its period of rotation was found to be 7.7 h. Moreover, it turned out to have a very dark surface, reflecting little more than three percent of the sunlight falling upon it. Reflectance spectra revealed it to be an object of the D-Type; falling within the broad class of carbonaceous objects but somewhat redder in color than the mainline C-Types. That taxonomic classification was not typical of Amor-type asteroids, but was more in line with those bodies inhabiting the outermost region of the asteroid belt as well as being characteristic of the Jupiter Trojans. It is also the reflectance spectrum most often recorded for quiescent comet nuclei, something that raised speculation amongst a number of astronomers that Don Quixote might be a "dead", or at least a "sleeping", comet.

It was clear however, that if this object is a comet in disguise, it is a large one. With an absolute magnitude of around 12 coupled with its very low albedo, the calculated diameter of the asteroid comes out at just under 19 km (approximately 12 miles)—quite a size for one of the asteroids that venture into the region of the innermost planets and certainly big by the standards of short-period comets.

The true nature of this strange body started to be revealed in 2009 when images at infrared wavelength were obtained with the *Spitzer Space Telescope*. These images did not appear to be as sharp as those of stars and further examination and enhancement showed that they were images of something more than a simple solid body reflecting sunlight. Don Quixote possessed a coma and a tail, albeit visible only at infrared wavelengths! This object is a genuine comet, neither dead nor even dormant, but simply possessing a *very* low level of activity. The infrared coma and tail imaged by Spitzer were visible because of CO_2 emissions and, given that frozen carbon dioxide is a rather minor constituent of comets compared with water ice, we might expect that a cometary body the size of Don Quixote stores quite a deal of the latter bur-

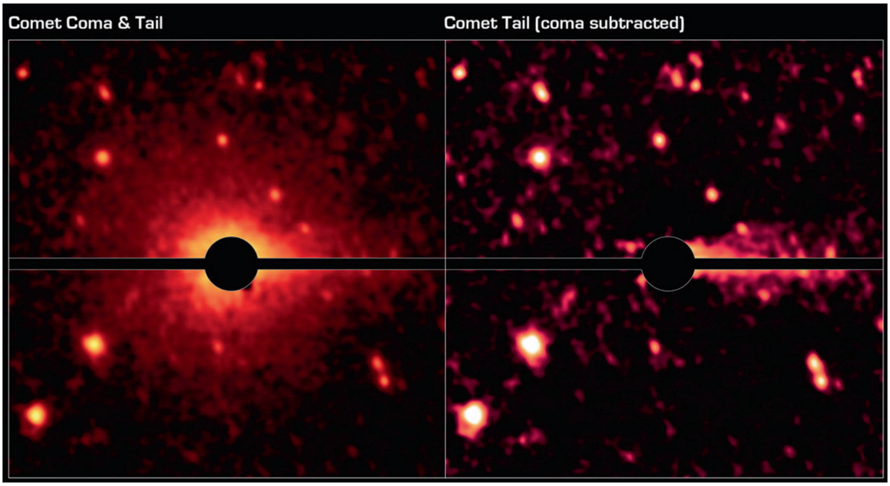

FIGURE 2.6 Coma and tail of asteroid 3552 Don Quixote as revealed at IR wavelengths. Credit: NASA/JPL-Caltech/NAU

ied beneath a thick layer of insulating crust. Indeed, it has been estimated that this object probably contains around 100 billion tons of water ice. If melted down, that amount would fill quite a decent-sized lake on Earth (Fig. 2.6).

In all probability, this object was once far more active, but during the course of many perihelion passages, it has built up a crust of non-volatile material which has largely choked off the sublimation of its underlying ices. Because its perihelion distance is not very small, the Sun's warming rays do not penetrate very deep down and most of its icy store remains as stable as rock. The comet appears to be dead—or almost dead; a mere shade of its presumably active former self. One might dare to call it a ghost comet!

Nevertheless, we might wonder as to what may happen if part of this body splits away from the main mass. This is possible, maybe through collision with another object or through some internal weakness. Either way, exposure of internal ice would presumably rejuvenate the comet to its (we suppose) former glory. The half-life of a ghost might one day become the rising of a phoenix.

Although there is no chance of this occurring in the foreseeable future, it is nevertheless interesting to speculate on what may happen should this object manage to get deflected through planetary encounters into an orbit having its perihelion distance as small as, say, Comet Encke. Moving from just beyond the orbit of Earth to just within that of Mercury would mean that the comet would be exposed to a greatly increased incidence of solar radiation. The Sun's heat would penetrate to depths unreached in the comet's present orbit and would, presumably, activate large quantities of ice, probably blowing away much of the insulating crust and changing Don Quixote from a very weakly to a strongly active comet. Conversely, if Encke could be transported out to an orbit having perihelion outside Earth's orbit, its activity would radically decrease and this object would undoubtedly enter a state of near or complete dormancy. Such considerations as these surely demonstrate the degree to which the orbit of a volatile-bearing object can determine whether it is listed as an asteroid or as a comet. To borrow the slogan of real-estate agents, it is often a matter of "location, location, location" as to which category objects of partially volatile compositions will be placed. An active comet with a perihelion distance close to that of Mercury may be exactly the same in terms of size and composition as an asteroid that ventures no closer to the Sun than the planet Mars!

On the evening of October 10, 2004, Rob McNaught at Siding Spring Observatory in New South Wales, found an apparently asteroidal object that was subsequently designated as 2004 TU12. Several pre-discovery images of the asteroid were later found on other sky-patrol and survey plates dating back to 1990, enabling a good orbit to be secured.

Images obtained at various observatories during the following month showed nothing out of the ordinary about this object however on November 12, 2 days after it passed through perihelion at 1.23 AU from the Sun, a tail was photographed by J. Lacruz and, also on that same day, this feature was likewise imaged at Las Campanas by G. Masi, F. Mallia and R. Wilcox.

Taken at face value, this suggests that the comet began to "come alive" following perihelion and to some degree recalls Ferrin's conclusion concerning the post-perihelic activity of Wilson-Harrington. However, throughout the days following the appearance of the tail, this feature was recorded as fading as well as becoming detached from the comet's head or nucleus (no actual "coma" was seen at any time). The transitory nature of the tail once again draws our mind back to Wilson-Harrington, this time to its 1949 return, although there are some notable differences as well. In this more recent instance, the tail was a little more durable and the Wilson-Harrington tail was not observed to separate and float away from the comet. As far as can be ascertained, the earlier tail simply faded away. The behavior of the tail 2004 TU12 does not accord with the type of tail flare suggested as a possible explanation for the earlier event and *may* be more supportive of the dust composition of the later tail, although gas tails have also been observed to detach from their parent comets. In any event, the tail of 2004 TU12 was not replaced by a new one and this led to some speculation that this object may not be a "true" comet at all but rather, a bona fide asteroid that just happened to be struck by a meteorite, raising a puff of dust, soon after it passed perihelion. That does seem a rather unlikely coincidence, but a more serious problem with that explanation was pointed out by S. Yoshida who found that the tail did not lie in the object's orbital plane, as would be expected for the coarse dust particles raised by a collision. Yoshida concluded that the feature was a "normal" tail resulting from true cometary activity, although he draws no conclusion as to whether it was more likely to have been composed of dust or of gas.

In accordance with the "Marsden rule" (if it has a tail, it's a comet) the "asteroid" was re-classified as a short-period comet and given the final designation 162P/Siding Spring. In accord with the rules concerning such matters, because it had initially been announced as an asteroid, it was given the name of the observing program ("Siding Spring" from the "Siding Spring Survey") and not the name of the discoverer, "McNaught".

It turns out that Siding Spring is not very much smaller than Don Quixote, having an estimated diameter of between 12 and nearly 14 km (about 7.5–8.8 miles). Unsurprisingly, it also has a very dark surface and appears to be essentially of the C-Type. Reflectance spectra obtained by H. Campins and colleagues detected evidence of amorphous carbon and some organic compounds, together with silicates, on the comet's surface.

At the time these words are being written, 162P's most recent perihelion passage occurred on July 11, 2015. The object appears to have remained quiescent, although an image obtained by Masi well after perihelion (on April 10, 2016 in fact) *may* have captured a very faint tail, a little clearer in the negative image than in the positive one.

November 28, 1819, witnessed the discovery of a new comet by astronomer J. Blanpain. There was nothing especially unusual about the comet's appearance, however once a reliable orbit was calculated, it was found to be moving in a strongly elliptical orbit, having a period of just over five years. The perihelion distance was computed to be 0.82 AU from the Sun, not very far within the orbit of Earth. Surprisingly however, nothing more was seen of the comet on subsequent returns and it was relegated to the limbo of the lost comets, together with such one-apparition objects as Helfenzrieder as well as other once-regular, but now vanished, periodic comets like Biela and Brorsen. With the introduction of the revised system of comet designations introduced in the mid-1990s, Comet Blanpain became officially known as "D/1819 W1 (Blanpain)", "D" covering "*d*isappeared", "*d*efunct", *d*ormant or "*d*ead"!

The next act in the Blanpain saga (although it was not recognized as that at the time) came in 2003 with the discovery of a small asteroid that was later designated as 2003 V25. This body had a perihelion distance just inside Earth's orbit and pursued a rather comet-like orbit having a period of 5.3 years. Two years later, David Jewitt found that the orbit of this asteroid bore a striking resemblance to that of Comet Blanpain and the apparitions of 1819 and 2003 were subsequently linked, showing that these "two" objects were in actual fact one and the same. Moreover, the comet turned out to be not quite defunct after all. Examination of the "asteroid" images revealed the presence of a very faint coma. In recognition of the comet's continuing existence, it was re-designated as "289P/Blanpain" in 2013.

According to Dr. Ferrin, Blanpain is rather similar to Wilson-Harrington in being an object of very low activity that is heading toward a state of dormancy. It is not, however, quite as far along the dormancy road as Wilson-Harrington, as the presence of a coma—albeit a very faint one—may still be detected surrounding the apparently asteroidal body.

It is unlikely that the bright discovery appearance of 1819 betrayed the last vigorous gasp of the comet. More likely, the comet was in outburst that year, briefly awaking from the quasi-dormant state that presumably had previously characterized its performance and into which it soon regressed and remained ever since. If that assessment is correct, another similar outburst is not impossible at a future return, although it must be admitted that the chance of this happening is not very great.

This comet is thought to be the parent object of a fairly strong meteor burst from the southern constellation of Phoenix that occurred on December 5, 1956. This meteor shower, thereafter known as the Phoenicids), caught everyone by surprise as nothing from that radiant had been noted earlier and the hourly meteor rates became pretty high—about 100 per hour at the peak of the display. Moreover, the stream was well endowed with bright objects. Many of the meteors were compared in brightness to the very brightest stars and planets and some even to the Moon. To add to the display, the fireballs were mostly of the exploding type known as "bolides".

Nothing to equal the 1956 display has, alas, been seen in more recent years, although from the early 1970s onward, several observers have detected the continuing presence of the shower around the end of the first week of December. Rates are a far cry from 1956, being only about five per hour, but it is nevertheless apparent that the shower of that year was not a one-off event as had been assumed during the years immediately following the display.

The existence of this meteor stream, especially the relatively dense swarm which Earth encountered in 1956, indicates that the comet has experienced higher degrees of activity—possibly in the form of brief but strong outbursts—in the not-too-distant past.

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