Comet Science

Mysterious Travelers

Humans have been seeing comets for millennia, but we still have a lot more questions than answers.

Photograph by Sebastian Deiries / ESO

COMET OVER PACIFIC Comet McNaught and its spectacular tail graced Southern Hemisphere skies in early 2007.

David Jewitt

Our knowledge of comets predates civilization. The brightest comets, infrequent and unnervingly unpredictable visitors to the inner solar system, were widely received by the ancients as omens of doom. Aristotle thought they were peculiar meteorological phenomena ("burning air"). At the dawn of modern science, Tycho Brahe demolished this notion by using parallax to show that the comet of 1577 was more distant than the Moon. Only in the past century have we come to understand the true significance of comets as icy relics from the epoch of planet formation. And only in the last few decades have we started to use comets as tools to understand the origin of our solar system.

Our modern view is best framed in terms of Fred Whipple's "dirty snowball" model. In this picture, a comet is a solid, ice-dirt conglomerate nucleus that sublimates (solid material vaporizing to gas) in the Sun's heat to form a transient, roughly spherical atmosphere, or *coma*. Radiation pressure from sunlight along with magnetic forces from the solar wind push dust and ionized cometary gases out of the coma, forming the dust and gas tails, respectively.

Beyond this broad-brush picture, our understanding of comets is very limited. Although the coma and tail can be very large and spectacular, most of the mass and scientific interest lies in the nucleus, which is small, faint, and very difficult to detect. A comet nucleus only a few miles in diameter sometimes produces a tail that stretches tens of millions of kilometers, comparable to the distances between the planets. The study of the nucleus is so difficult that the first reliable telescopic measurements were obtained only in the 1980s, at about the same time that the European Space Agency's Giotto spacecraft returned the first close-up pictures of Comet Halley's nucleus.

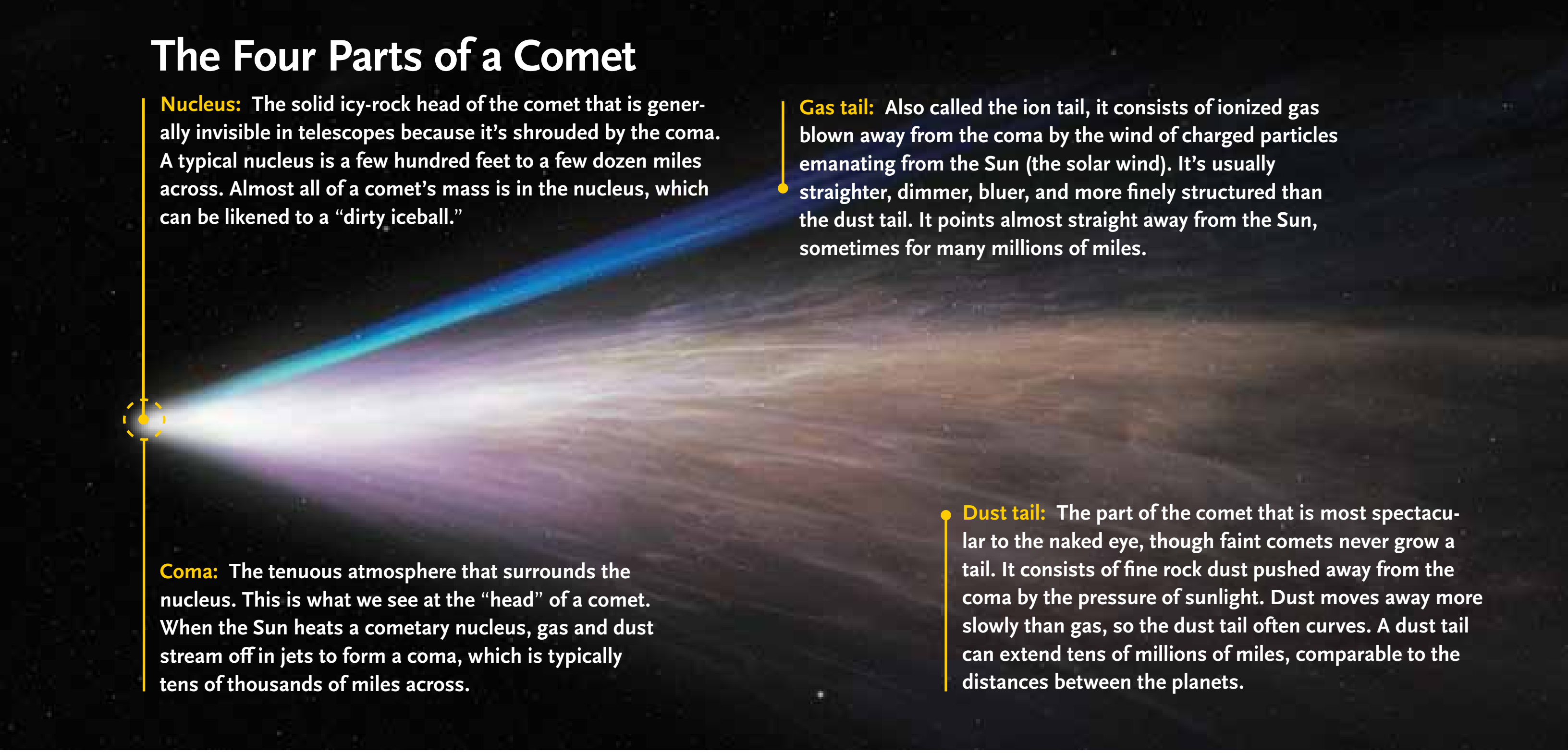
Even though people have seen comets for millennia, the meaningful scientific investigation of these iceballs is a comparatively new endeavor. These visitors from distant realms still present us with perplexing mysteries.

Fresh from the Freezer

Comet nuclei are small, but they can shed mass at prodigious rates. For example, Comet Halley, with an effective nucleus diameter of about 11 kilometers (7 miles), loses 50 to 100 tons *per second* at each perihelion owing to sublimation. At this rate, such a small body would run out of material in a few tens of thousands of years, far less than the 4.5-billion-year age of the solar system. In principle, this could mean that comets are young, but in practice there is no place in the modern-day solar system where comets can form.

Instead, comets are primordial bodies that formed at low

The Four Parts of a Comet



Nucleus: The solid icy-rock head of the comet that is generally invisible in telescopes because it's shrouded by the coma. A typical nucleus is a few hundred feet to a few dozen miles across. Almost all of a comet's mass is in the nucleus, which can be likened to a "dirty iceball."

Gas tail: Also called the ion tail, it consists of ionized gas blown away from the coma by the wind of charged particles emanating from the Sun (the solar wind). It's usually straighter, dimmer, bluer, and more finely structured than the dust tail. It points almost straight away from the Sun, sometimes for many millions of miles.

Coma: The tenuous atmosphere that surrounds the nucleus. This is what we see at the "head" of a comet. When the Sun heats a cometary nucleus, gas and dust stream off in jets to form a coma, which is typically tens of thousands of miles across.

Dust tail: The part of the comet that is most spectacular to the naked eye, though faint comets never grow a tail. It consists of fine rock dust pushed away from the coma by the pressure of sunlight. Dust moves away more slowly than gas, so the dust tail often curves. A dust tail can extend tens of millions of miles, comparable to the distances between the planets.

CASEY REED

temperatures in the outer solar system and have been stored in deep freeze ever since. Short-period comets come from the Kuiper belt (where temperatures are about –230°C, or –380°F) whereas most long-period comets originate in the Oort cloud (about –260°C). Comets are dislodged from these reservoirs by gravitational disturbances from the planets (in the case of the Kuiper belt) and from passing stars and the galactic tide (Oort cloud).

However, infrared spectral observations of comet dust seemingly contradict the idea that the nuclei are frozen remnants from the time of planet formation. Silicate dust grains in comets show clear evidence of having been heated to temperatures near 1000°C. This is even hotter than a mid-day on Mercury, yet the comets ejecting these grains have never been that close to the Sun. If they had, their water ice and other volatile materials would have vaporized long ago. Even more perplexing, NASA's Stardust mission found a calcium-aluminum inclusion (CAI) in dust from Comet Wild 2's coma. CAIs are minerals formed at high temperatures that were previously found only in meteorites from the asteroid belt. We recognize them as the first solids that condensed as the inner solar nebula's hot gases cooled.

How could comets be ice-rich and yet contain dust that has been very strongly heated? The answer seems to be that the Sun's protoplanetary disk was strongly mixed; hot dust particles near the young Sun were somehow transported to the outer regions, where they were encased in ice and then trapped in cometary nuclei.

Geology on a Dirty Snowball

Although a dirty-snowball nucleus seems simple, it's replete with unexpected complexity. Telescopic comet images offer a hint of this by showing jets and other structures in the coma. We think jets erupt because sublimating ice is confined to limited active areas (vents), whereas most of the nucleus's surface is blanketed by inert material (probably rocks too big to be ejected from

SHORT- VS. LONG-PERIOD COMETS

Short-period comets are those that take less than 200 years to orbit the Sun. Long-period comets take 200 years or more to complete an orbit.

COMET HALLEY On March 13, 1986, ESA's Giotto spacecraft flew by Comet Halley at a range of only 596 kilometers (370 miles) and returned the first-ever close-up shot of a cometary nucleus. This image shows jets of gas and dust streaming away from the 15-by-8-km-wide nucleus.

ESA / MPAE / LINDAU

the nucleus by gas drag). During Comet Halley's 1986 apparition, for instance, jets fed the coma through only about 10% of the surface. But Halley was unusually active, and on many other comets the active regions can cover as little as 1%.

Moreover, the actual surfaces of cometary nuclei turn out to be very puzzling geologically. Features seen in high-resolution nucleus images are unlike those found anywhere else in the solar system.

The biggest surprise is that images of cometary nuclei show little evidence for vents or active areas. For example, in a picture of Comet Wild 2's nucleus from NASA's Stardust mission, one could not guess the locations of the jets in the coma. The same goes for a NASA Deep Impact spacecraft image of Comet Tempel 1. Wild 2's nucleus has so many craters that it's tempting to think they were formed by impacts, like those seen on the Moon or asteroids. But they are much deeper in proportion to their widths, they are not bowl shaped, and some even have vertical walls with overhangs. Conceivably, some of these strange features are the products of small projectiles striking very porous materials. More likely, the craters were not formed by impacts at all. They could represent collapse features, caused by the past loss of near-surface volatile materials in jets. We simply don't know.

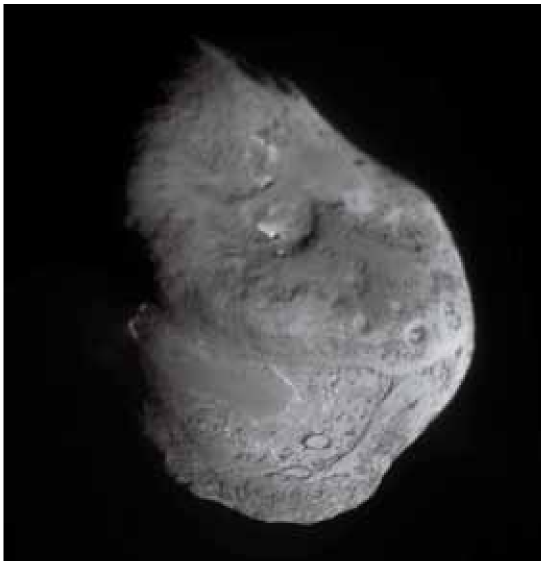
Another surprise is that the spacecraft-imaged nuclei differ considerably from one another. Tempel 1 shows very few craters compared to Wild 2. Its surface is distinguished by smooth regions that resemble flows of low-viscosity material. We don't know what these flows are. In one model, they consist of dust fluidized by gas leaking from the nucleus that is unable to escape the comet's feeble gravity (the escape speed from Tempel 1 is so low — about 1 meter per second — that an overly enthusiastic astronaut could jump off without the aid of rockets). In contrast, Comet Hartley 2's nucleus exhibits a weird composite structure, suggesting that it was constructed when different objects stuck together.

Exploding Ice

Another mystery concerns the physical form of the ice in comets. In the normal ice you find in your refrigerator, the water molecules are arranged in an orderly, hexagonal structure. We call that *crystalline ice.* But at the low temperatures typical of the Kuiper belt and Oort cloud, the ice can be *amorphous,* in which the water molecules occupy a chaotic jumble, devoid of any orderly arrangement. The difference between crystalline and amorphous ice might seem esoteric and unimportant. After all, ice is ice. In fact, the difference is potentially explosive! When amorphous ice is heated, for example in a comet moving closer to the Sun, it converts spontaneously to the crystalline form, releasing energy in the process. Moreover, the nooks and crannies between water molecules in amorphous ice offer excellent pockets for atoms and molecules

POCKMARKED COMET NASA's Stardust spacecraft took this close-up of Comet Wild 2's 5-km-wide nucleus on January 2, 2004. The many pits were probably formed by the collapse of solid material after venting rather than by impacts.

NASA / JPL-CALTECH



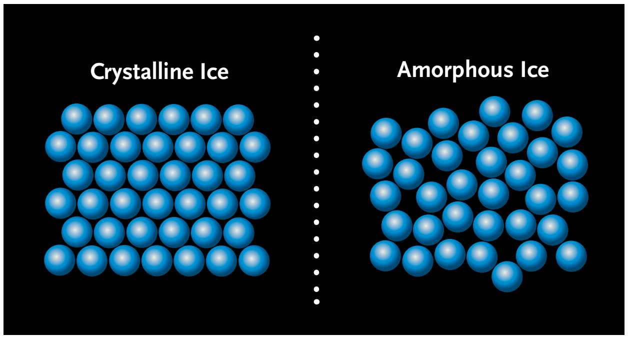
SMOOTH COMET When NASA's Deep Impact spacecraft flew by Comet Tempel 1 in July 2005, it revealed a remarkably smooth nucleus with only a few large collapse pits — a stark contrast to Comet Wild 2's nucleus. The longest dimension is 7.6 km.

NASA / JPL-CALTECH / UNIVERSITY OF MARYLAND

CONTACT BINARY After NASA's Deep Impact mission was renamed EPOXI, it flew by Comet Hartley 2 on November 4, 2010, and took this picture of what appears to be a contact binary: two pieces connected by a smooth, dust-covered bridge. The nucleus is only 2.2 km long. Note the venting jets at the far right.

NASA / JPL-CALTECH / UNIVERSITY OF MARYLAND

OUTBURST *S&T* imaging editor Sean Walker took this image of Comet Holmes with a 4-inch Newtonian astrograph on November 10, 2007. In just 42 hours in October 2007, Holmes brightened by nearly a million, reaching magnitude 2. The cause of the outburst remains unknown, but it may have been due to amorphous ice spontaneously converting into crystalline form.



S&T: LEAH TISCIONE

TWO FORMS OF ICE Water ice occurs in two forms. In its more familiar crystalline form (left), the molecules form an orderly, hexagonal arrangement. But in extreme cold, the molecules can be bunched together in a chaotic jumble (right). Various gases can become trapped in the gaps between molecules. When this amorphous ice is heated and spontaneously converts to crystalline form, it can explosively release the trapped gases.

of other gases to hide, making amorphous ice a kind of sponge for soaking up carbon monoxide, carbon dioxide, and other gases common in comets.

In addition to releasing energy, the rapid crystallization of amorphous ice squeezes out the trapped molecules, leading to potentially explosive outgassing. This might explain cometary outbursts such as that seen in Comet Holmes in 2007, which brightened nearly a million times in less than a day. Models suggest a runaway, in which heat released by the crystallization of one chunk of ice triggered the crystallization of adjacent ice, until all the nearby amorphous ice was consumed. Other comets have also exhibited outbursts (such as Schwassmann-Wachmann 1, which produces several outbursts per year), but not at the extreme level shown by Holmes. We don't know why this otherwise unremarkable comet produced such an atypically large outburst. Crystallization might also explain outgassing from comets that are too far from the Sun for crystalline water ice to sublimate.

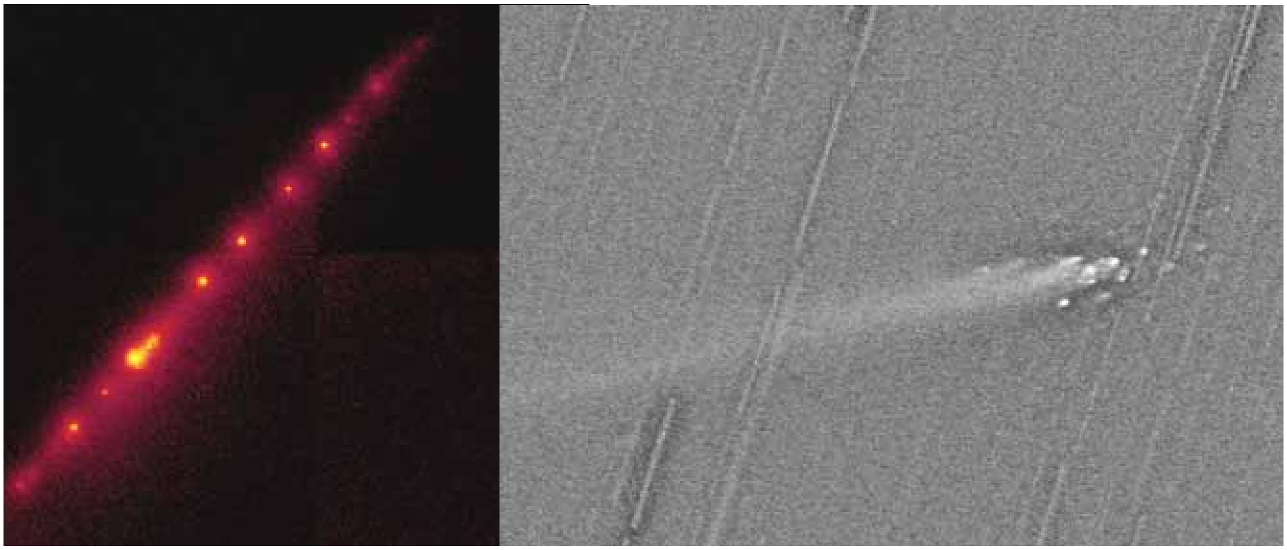
Unfortunately, we lack direct proof that comet ice is amorphous. If comets from the Kuiper belt contain amorphous ice, then it's reasonable to expect that the Kuiper belt objects themselves should be amorphous. Curiously, all reliable measurements of Kuiper belt objects show that their ices are in crystalline form.

When Breaking Up Is Easy To Do

Yet another cometary mystery is why nuclei break up, typically releasing a single companion object but sometimes disintegrating into a cluster of fragments or even a shower of dust. Our understanding of this phenomenon is negligible for most cometary disruptions.

We can explain a few cases by the breakup of the nucleus from gravitational stresses during a close flyby of the Sun or Jupiter. In the most famous example, Comet Shoemaker-Levy 9's "string of pearls" resulted from the nucleus of a comet that flew inside Jupiter's Roche limit and was ripped apart by gravitational stresses. Sungrazing comets, such as the recent and spectacular Comet Lovejoy, might also have suffered gravitational disruption. These mostly tiny objects, now numbering more than 2,000, are fragments of a large precursor nucleus that broke apart long ago. Models suggest that this nucleus was a rubble pile — a series of chunks held in contact by gravity and little else.

But other comets break up far from the planets or the Sun, where gravitational stresses are unimportant. One possible cause of these breakups is rotational disruption. A cometary nucleus vents gas preferentially on the dayside, exerting a net torque. Outgassing forces can be particularly strong for small nuclei, pushing the nucleus away from its Keplerian orbit and spinning it up in just a few orbits. Spin-up has been observed in several comets, most notably in Hartley 2. There, the torques exerted by sublimation changed the 18.3-hour rotation period at a



S-L9 IMAGE: HAL WEAVER / T. E. SMITH / STSCI / NASA; LINEAR IMAGE: ESO

COMET BREAKUPS Numerous forces can cause cometary nuclei to disintegrate. *Left:* In July 1993 the Hubble Space Telescope took this image of Comet Shoemaker-Levy 9's "string of pearls," kilometer-size fragments that resulted from the comet's tidal disruption by Jupiter about a year earlier. *Right:* Europe's Very Large Telescope acquired this dramatic image showing the breakup of Comet LINEAR in August 2006. LINEAR's fragments are much smaller than those of S-L 9. The cause of LINEAR's demise remain unknown, since it was not passing near the Sun or a planet when it broke apart.

ROSETTA RENDEZVOUS In mid-2014, ESA's Rosetta spacecraft will rendezvous with Comet Churyumov-Gerasimenko. It will deploy a small craft that will attempt to land on the nucleus.

ESA / AOES MEDIALAB

rate of nearly 1 minute per day in 2011. This change is extremely rapid in astronomical terms and could spin the nucleus to break-up speed in only a few orbits. Rotational breakup is probably one of the dominant mechanisms by which comets fragment and die.

What's Inside?

Spacecraft images also raise questions about the internal structures of cometary nuclei. If comets are collisional shards of Kuiper belt objects, then we expect them to have internally fragmented, rubble-pile-type interiors. Internal fractures would make the nuclei very weak in tension, consistent with their propensity to split and disintegrate.

But other nuclei may be quite different. In Deep Impact images, Comet Hartley 2 resembles a smooth-waisted, asymmetric dumbbell, suggesting to some that it's actually a *contact binary* (two independently formed objects resting against each other), with dust collected in the neck between the components. Furthermore, the gases sublimating from Hartley 2 are different at the two ends, with the small end releasing more carbon dioxide (CO_2) than the other. The different compositions suggest that the two pieces formed at different locations in the protoplanetary disk, with the more-CO_2-rich end forming farther from the Sun.

Michael Belton (Belton Space Exploration Initiatives) has proposed a totally different structure for other cometary nuclei, based on the flat, plate-like structures seen on Tempel 1. In his TALPS model, the nucleus is built like a stack of pancakes, with each incoming cometesimal flattened against the surface of the stack upon impact (TALPS is "splat" spelled backward). In the absence of better data probing nuclei interiors, we have no way to decide amongst these and other structure models.

These are still early days in the study of cometary nuclei. We know where these bodies have been stored in the solar system for billions of years. And we have characterized a few examples in enough detail to know that the physical properties of cometary nuclei are incredibly diverse. But we don't know why. How much of this diversity reflects modification of the nuclei on their long journeys from the Kuiper belt and the Oort cloud toward the Sun, and how much is primordial? Telescopic observations at different stages of their inward drift will shed light on this question in the coming decades.

A harder nut to crack is the question of how comet nuclei were built. Are they collisional shards from colliding Kuiper belt objects, are they rubble piles, Belton's pancakes, some combination of these models, or something entirely different? The answer will tell us how dirty snowballs accreted in the outer regions of the protoplanetary disk.

Resolving the internal structure might be possible with radar tomography, in which long-wavelength radio waves are transmitted through the nucleus to a detector on the other side. The first experiment of this type is planned for the nucleus of Comet Churyumov-Gerasimenko. If all goes well, a transponder on the landing portion of ESA's Rosetta spacecraft will send radio signals through the nucleus to be detected from the orbiter above. Never tried before, this measurement will open an entirely new and fascinating avenue for investigating comets. ✦

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For up to date information about Comet ISON, visit skypub.com/ISON.

NASA / ESA / LASCO

What Can We Learn from Comet ISON?

The long-period, sunskirting Comet ISON is headed toward a perihelion at 0.0125 a.u. (only 2.7 solar radii). If the nucleus survives its close encounter with the Sun, intense solar heating should produce a spectacular show, although the comet will be so close to the Sun that specialized instruments might be needed to view it. Most sungrazers do not survive beyond perihelion because they are only a few tens of meters across. ISON's nucleus is estimated to be 2 to 3 km in diameter, giving it a better chance. Planetary scientists will be watching to see how ISON's nucleus fares in the intense environment of the Sun's inner corona. Even if ISON's nucleus does not vaporize, it might break up or disintegrate from gravitational stresses imposed on it by the Sun. Careful measurements of the fragments will be useful in calculating the nucleus's internal strength.

SUNGRAZER The above image of Comet SOHO-6 is representative of many sungrazing comets discovered in SOHO pictures. Some comets barely survive their close encounters with our solar system's host star, whereas others disintegrate due to heat and/or gravitational disruption. SOHO-6 died a fiery death as it plunged into the Sun. It's an open question whether Comet ISON will survive its late November close encounter with the Sun.