On Comets

In the beginning

History is supposed to teach us lessons. There's one lesson that the history of comets writes in large letters, indeed shouts from the pages of the past: *don't trust what authorities say unless it's backed up by clearly linked evidence*. Unfortunately you just have to read the newspapers today to see that there is no shortage of people who believe the unfounded assertions of would be opinion makers. I'll leave you to think of your own examples. Why should comets have taught us this important lesson?

A comet is a moderately rare phenomenon in the sky for naked-eye observers. One distinct example every few years is typical. From Babylonian times (and probably before) until the Middle Ages, objects in the sky were the instruments of astrology. Almost everyone believed in astrology, from emperors, kings and rulers, elected or otherwise, through to the 'common people'. Comets were interpreted through the astrology of the day. Since comets were exceptional, they were portents of the exceptional. Almost universally they were thought to presage disaster. Listen to the much quoted Latin author Marcus Manilius in his work *Astronomica* "…Heaven in pity is sending upon earth tokens of impending doom, for the fires wherewith the heavens blaze have never lacked significance, but farmers cheated of their hopes, mourn over blighted fields, and amid barren furrows the weary ploughman vainly urges to the yoke his drooping team. … Death comes with those celestial torches, which threaten earth with the blaze of pyres unceasing[1]…". He goes on in this vein citing military disasters that have followed comets. On other occasions he cites, storms, floods and pestilence, echoing Aristotle's view that comets were a 'sublunary' phenomenon occurring in the high atmosphere. Aristotle in his *Meteorologica* had been more logical than most. Having identified comets as a burning phenomenon in the upper atmosphere he grouped them with other transient phenomena such as storms, exceptional tides and earthquakes, arguing that one of these is likely to follow the appearance of a comet. Manilius, though very definite in his statements, does recognise that the interpretation of signs varied among practitioners. Caveats aside, the widespread view was that comets were sent by the gods as omens.

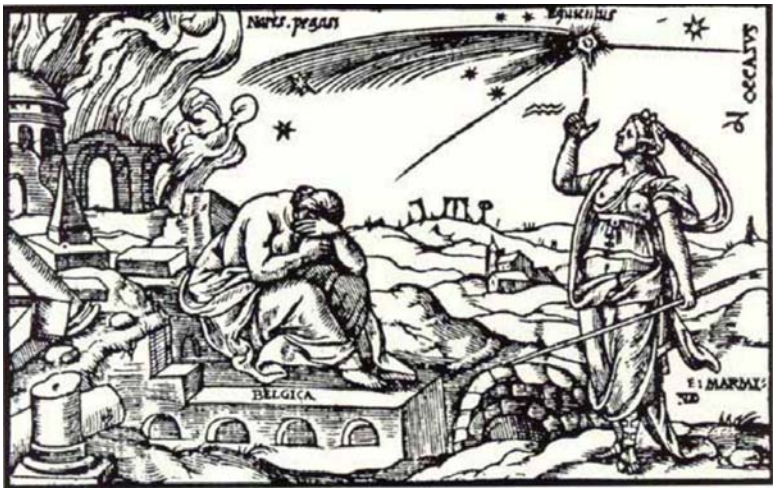
Such was the history of Roman emperors dying in close proximity to the appearance of a comet that when one appeared during Nero's reign he arranged to appease the fates by having his political opponents put to death, hoping to deflect the vengeance of the comet. The belief was more subtle than merely thinking that comets caused disasters. That was unlikely. They were signs from the gods to warn of the future. It was all complete nonsense, as we now know. The Romans in particular may have been hard-nosed practical people but it was an era of belief in fantasy too, when men thought they could divine the future by examining entrails and influence the future by sacrifices.

[1] This and some other historic quotes come from Sara J. Schechner's compendious "Comets, Popular Culture, and the Birth of Modern Cosmology" [Princeton University Press, 1997]. As well as reproductions of many ancient woodcuts, it contains over 80 pages of academic notes and a bibliography of over 800 reference works.

The ancient civilisations teased out the rules of logic and applied them to their philosophy, their laws, their military campaigns and to some extent their arts. Yet they continued to associate a spurious significance to comets without any causal linkage. You might have thought that it would all change when a new religion diffused through the western world in the early centuries AD. The old temples and their effigies crumbled; the new religion had no effigies of God and his emissary. The new religion may have claimed to be nearer the truth but it failed to ditch the idea that comets were a sign from God of future disasters. Not only did they presage natural disasters in the Aristotelean vein but in addition foretold the fall of kings, the destruction of cities, the desolation of nations. In fact as a public spectacle visible across countries they foretold disasters on a national scale. Did not Halley's comet appear brightly in 1066 before the demise of the Anglo-Saxons? It's shown in the Bayeaux tapestry. Of course disaster for one party might well have been triumph for another, but that's a minor detail. Comet tails illustrated as sword-shaped helped to bring home the message of comets as the harbingers of violent and abrupt change. It was still all complete nonsense, as we now know.

That said, the nonsense did continue for centuries after 1066. Everyone was at it from the writers of cheap broadsides, pamphlets and chapbooks to the authors of almanacs and serious academic volumes. The 16th and 17th centuries saw prolific examples. Comets now predicted the untimely end of notable religious people and were soon cited as signs from on high that the public were morally lax and needed coercing back onto the straight and narrow path of righteousness. Andreas Celichius drew on the upper atmosphere notion of comets: "*the thick black smoke of human sins, rising every day, every hour, every moment, full of stench and horror, before the face of God, and becoming gradually so thick as to form a comet, with curled and plaited tresses, which at last is kindled by the hot and fiery anger of the Supreme Heavenly Judge*". I think the modern verdict would be 'psychologically disturbed'. Nonetheless, in less inflammatory language statesmen, the learned clergy and astronomers themselves were invoking comets as signs from God. Up until at least the time of Tycho Brahe and Johannes Kepler, astronomers were also astrologers.

During the reformation, Protestants took comets as a sign that Popish religion was doomed. Martin Luther wrote "whatever moves in the heaven in an unusual way is certainly a sign of God's wrath. The heathen may ascribe natural causes to comets but they were created by God to instil terror". John Knox preferred to think they just augured 'mischief'. Picking just one example of a



Wood cut by Cornelius Gemma showing the comet of 1577 being pointed to by the goddess of fate while Belgium weeps over war and destruction.

more general prediction for the 1680 comet, William Knight wrote that the comet portended "*fear, trouble, grievous sickness, plague, consumption, agues, lingering distempers, tempestuous winds, shipwrecks, inundations, frosts and snows, and the destruction of fruits by worms and caterpillars.*" Since most of these things probably happened, people continued to believe. If one astrologer's 'predictions' failed, you could probably find another's predictions that had come true. The connection of these social ills to comets was still all complete nonsense, as we now know.

The message I take home from all this is that we really don't like having no explanation for something. Rather than acknowledge ignorance we will believe an assertion that can't be disproved at the time. This doesn't just apply to comets. Unfortunately, leafing through the pages of history we can find many people whose untimely deaths have originated in the holding of false beliefs, by them or their persecutors.

One wit said that without doubt comets were responsible for arguments amongst astronomers. There were arguments over whether comets were sublunary or above the Moon. There were arguments over whether kings and nobles were particularly threatened by comets or whether everyone was but people only remarked on the downfall of the powerful. There were certainly arguments as to whether comets actually caused disasters or merely adumbrated them. So when did the light finally dawn on what comets really are? Peter Apian in the mid-1500s noted that comets tails pointed away from the Sun. This is not immediately obvious because most comets are seen only after sunset. Tycho Brahe in particular demonstrated that the great 1577 comet was definitely not sublunary by effectively noting from observations as far apart as Hven and Prague that it had little parallax, whereas the Moon did. With comets now located amongst the planets if not the stars, this still didn't rob them of their ability to foretell events, for did not the planets also travel in orbits and influence the affairs of men, as all astrologers affirmed? If you wanted to believe that the 1664 and 1665 comets were a warning to the citizens of London that unless they mended their morals their houses would be burnt to cinders in 1666, then probably nothing would dissuade you as you surveyed the ashes of the great fire. Millennia of the abuse of comets did not evaporate suddenly. By then, however, even those who defined both Protestant and Catholic orthodoxy were beginning to distance the church from astrology and its claims to unveil God's intentions.

As Newton himself deduced in the 1680s once he had realised the significance of 'universal gravitation', though planets travelled in near circular orbits, comets could travel in highly elliptical orbits, so there were physical reasons why comets behaved differently from planets. Halley and others made it very plausible that some historic comets were re-sightings of the same object that returned periodically. Astronomers and commentators were collectively engaging their eyes and brains in the late 1600s, not only observing more diligently but querying by what mechanism comets were supposed to foretell future events. There were still sticking points. Christian theology is deeply teleological. So what purpose did comets have?

Theological questions aside, the heathens, to use Martin Luther's word, were being proved right. When it came down to it there was neither mechanism nor evidence that God put

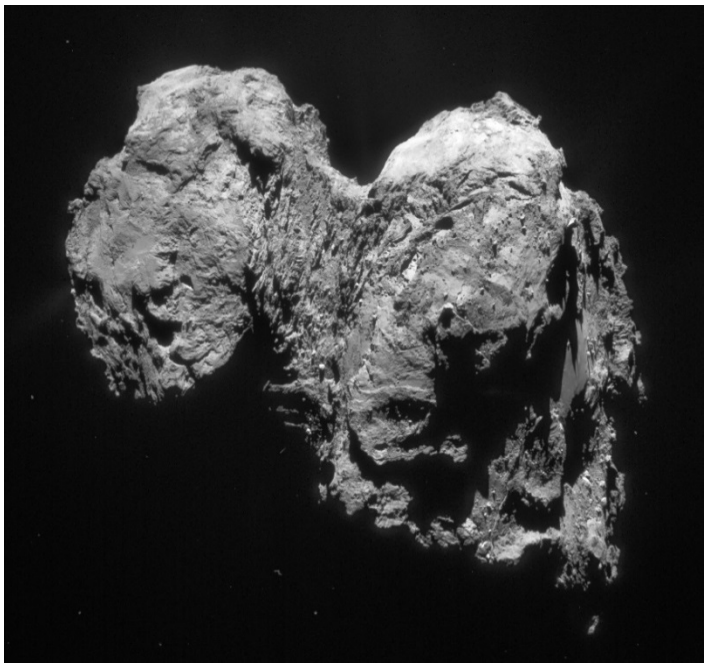
comets in the sky to warn of imminent natural or moral catastrophes. Disasters happened whether comets appeared or not. By the end of the 1700s, comets were generally seen as just another kind of object in the sky. God was not completely banished by all commentators, for as one wrote after pointing out that the fiery tail was a mechanism for dissipating the heat from the Sun "*and that the additional heat thus issuing from these bodies prevents an accumulation unfavourable to animal existence, supposing these bodies to be inhabited, as we have great reason to do, seeing that God has created nothing in vain*". The religiously minded were hanging on by their fingertips. Comets as auguries were dead, though. In the first half of the nineteenth century people could name their pioneering steam boat or railway locomotive 'Comet' without implication that passengers were in for a disastrous ride.

One development that Newton and his contemporaries began was the introduction of appropriate concepts. Without appropriate concepts explanations are usually a mess. One very simple example is that comets used to be called 'bearded stars'. Stars emit their own light, therefore without any conscious deduction comets were thought to do so too. Wrong. They are not bearded stars. Gravitation and the laws of motion were two appropriate concepts introduced by Newton. He also made clear the importance of numeracy, an aspect that took a long time to be recognised. A popular idea in the 18th century was that planets condensed out of a nebula of gas and dust. Comets had a nebulosity around them, therefore comets condensed into planets. Wrong. Had 18th century astronomers put reasonable numbers into their observations they would have realised that even the smallest planet had at least a million times the mass of a comet. Appropriate concepts and numeracy underpin modern science's take on comets, and indeed most natural phenomena.

Astronomically there were still many unknowns about comets in the 19th century, unknowns that would not be discovered until into well into the following century. What were they made of? How big were they? How were their tails formed? This brings us to where today's astronomy books come in.

The modern take

What makes us convinced that we now understand in some detail what comets are? First and foremost, we've looked more closely than our ancestors were ever able to. Comet nuclei can be probed in size and rough shape by radar. The chemical make-up of the gases subliming from comets and molecular species excited by solar radiation can be analysed using spectroscopic techniques at Earth-based telescopes. These now cover radio, infrared, visible and UV regions of the spectrum. We know broadly



The nucleus of 67P/Churyumov-Gerasimenko: courtesy ESA

what comets are made of. We've applied numeracy and the concepts of optics to deduce that the coma and tail are incredibly diffuse, in fact containing really low densities of matter. Laplace had the right idea in the early 19th century. Even more impressively, we've been there. The space-probe *Giotto* (amongst others) flew close by the nucleus of Halley's comet in 1986, photographed and measured it. *Deep Impact* flew close enough to comet Tempel 1 in 2005 to fire an impactor into its nucleus to eject a large cloud of material from below the surface that was analysed. *Deep Impact* went on to photograph the nucleus of comet Hartley 2 in 2010. *Stardust* collected cometary dust material in 2004 from comet Wild 2, returning some to Earth before going on to intercept Tempel 1 and image its nucleus in 2011. *Rosetta* has been flying alongside comet 67P/Churyumov-Gerasimenko, orbiting it for some 2 years as I write this, mapping it, examining its emissions as it went round the Sun and putting down the Philae lander onto its surface. We have now seen comets up close and personal and smelled their breath. They aren't all the same.

Hale-Bopp in 1997 showing a faint blue ion tail and short dust tail: courtesy Wikipedia

Most comets are visible only with the aid of a telescope (something of a blunder by any gods sending comets as a means to forewarn mankind). What is visible is the head of the comet and its tails. The visible head is the *coma*, a cloud of particles that may be well over 100,000 km across surrounding a solid nucleus of typically a few tens of km. A comet is likely to have two tails when it's near the Sun. One thin tail runs out straight on the continuation of the line from Sun to comet. This is the 'ion tail' created by tiny ionized particles swept out by the solar wind at a few hundred km per second. The other tail is the fatter 'dust tail' that may be curved. This is composed of larger debris ejected in jets from areas of the nucleus. It may be short or long, depending on how dusty the nucleus is. The dust in the tail is pushed away from the Sun by radiation pressure and it also has the velocity of the nucleus and any ejection speed. All these factors vary with distance from the Sun, resulting in a slightly curved trail of exhaust debris generally pointing away from the Sun. Comets and their tails are not 'fiery' at all. In fact any comet that gets no closer to the Sun than the Earth (like 67P/Churyumov-Gerasimenko) will not even reach an average temperature as high as the freezing point of water. Surface areas temporarily in the full blaze of the Sun's rays will get a bit hotter but as soon as the rotation of the nucleus

puts them in shadow, a few hours later, then their temperature will plummet. In fact repeated 'thermal shock' is thought to be a significant mechanism responsible for cracking the surface.

The orbits of thousands of comets have been computed and we understand where they come from. There are two sources, both of them in the cold outer reaches of the solar system. The first is the Kuiper belt, an extended region outside the orbit of Neptune roughly in the plane of the planets but spread above and below more widely than the planets. Most Kuiper belt objects never come near the Sun but disturbances within the Kuiper belt as two or more bodies come close together can send an object in towards the Sun. This appears as a 'short period' comet, short in this case being no more than a century or two. Fortunately for us, it will be the smaller objects that will be given a large perturbation necessary to send them to the inner solar system. Halley's comet is a Kuiper belt object with aphelion a few astronomical units bigger than Neptune. Its period is about 75 years. Kuiper belt comets have orbits that are reasonably close to the plane of the solar system. The other source of comets is the much more distant Oort cloud, a spherical cloud of objects stretching from 1000 to 100,000 astronomical units from the Sun. Oort cloud comets have periods of thousands of years and can come in from any direction. Hale-Bopp was an Oort cloud comet, possibly recorded 4200 years ago by the Egyptians but now perturbed a bit by Jupiter and expected again in some 2500 years time.

Fred Whipple is credited with putting forward the 'dirty snowball' model in the early 1950s for the consistency of a comet nucleus. The results of the space probes suggest that there is more rocky material than ice in the nuclei that have been visited – that they are more like 'icy dirt-balls'. The Philae lander failed to anchor as planned when dropped onto 67P/Churyumov-Gerasimenko because the surface was too hard for the anchor bolts. *Deep Impact* had puffed up the surface of Tempel 1 as if it were talcum powder but it's not entirely surprising that comet surfaces may he very hard, for during most of a comet's orbit its temperature could well be less than -200°C and even its ices will be 'rock hard'. In spite of being generally dark in colour and illuminated by the Sun, comets are poor conductors of heat and will be slow to warm beneath the surface. The original agglomeration will lose more ice than rock when the jets become active near the Sun and even when the comet is further away its ice sublimes from the surface. Comet nuclei are highly irregular in overall shape and in surface texture, containing few impact craters but many cliffs, chasms and boulders of varying size resting on the surface. The nuclei slowly rotate.

So much for some of their physical characteristics. The solids on comets that give rise to gases when heated include the big two, water and carbon monoxide, followed by many other species including carbon dioxide, methane, ethane, acetylene, ammonia, hydrogen cyanide, hydrogen sulphide, sulphur dioxide, methanol, formaldehyde and more - a pretty toxic mix of substances! Cometary dust includes compounds of carbon, hydrogen, oxygen and nitrogen along with minerals including sodium, magnesium, calcium and iron. In addition both amorphous and crystalline silicates are present. Perhaps not surprisingly, there are carbon rich and carbon depleted comets, just as there are asteroids. The composition of comets is a key indicator of their formation conditions.

Comets don't last more than a few hundred orbits before their material has been dispersed and the remnants broken up or perhaps plunged into the Sun or a planet. Jupiter is the most likely planet. This implies that they have spent most of their lives in 'cold storage' in the outer solar system. When they started out as comets they were representative of material aggregated in the very early stages of formation of the solar system. Since planetary system formation is a hot topic in today's astronomy with the discovery in recent decades of thousands of diverse planetary systems around other stars, cometary studies are particularly topical.

Knowing what we do today about comets, one can't help but be amazed at the amount of nonsense that has been written and no doubt spoken about comets over the centuries. People pontificated, vehemently at times, with assertions on what comets were, what their purpose was, what their effects on the Earth and mankind were without a shred of evidence or understanding of what comets actually were. Lack of understanding is quite forgivable in the absence of facts. Making up stories is relevant in the realm of the creative arts but presenting them as the definitive truth of how nature is organised is surely unforgivable. The history of ideas on comets is a ripe example of how wrong people have been in the past in their understanding of nature.

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