The Origin of Comets and the Oort Cloud

Comets from Ancient Times to the Modern Era

Mark E. Bailey
Armagh Observatory

http://star.arm.ac.uk/
meb@arm.ac.uk

Table of Babylonian/Greek/Roman Theories of Comets

<table>
<thead>
<tr>
<th>Date</th>
<th>Broad Type</th>
<th>Originator</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.2000 BC</td>
<td>Celestial</td>
<td>Babylonians</td>
<td>Earthy bodies akin to planets</td>
</tr>
<tr>
<td>c.2000 BC</td>
<td>Celestial</td>
<td>Babylonians</td>
<td>Fiery celestial phenomena</td>
</tr>
<tr>
<td>c.575 BC</td>
<td>Celestial</td>
<td>Anaximander</td>
<td>Jets from fiery celestial hoops</td>
</tr>
<tr>
<td>c.575 BC</td>
<td>Atmospheric</td>
<td>Xenophanes</td>
<td>Burning clouds</td>
</tr>
<tr>
<td>c.450 BC</td>
<td>Celestial</td>
<td>Anaxagoras</td>
<td>Planetary 'conjunctions' on sky</td>
</tr>
<tr>
<td>c.450 BC</td>
<td>Celestial</td>
<td>Pythagoreans</td>
<td>Rare sighting of a planet</td>
</tr>
<tr>
<td>c.430 BC</td>
<td>Celestial</td>
<td>Hippocrates</td>
<td>A kind of planet</td>
</tr>
<tr>
<td>c.430 BC</td>
<td>Atmospheric</td>
<td>Pythagoreans</td>
<td>Reflected sunlight</td>
</tr>
<tr>
<td>c.430 BC</td>
<td>Celestial</td>
<td>Diogenes</td>
<td>Chains of rocky bodies (stars)</td>
</tr>
<tr>
<td>c.400 BC</td>
<td>Celestial</td>
<td>Artemidorus</td>
<td>Chains of unseen planets</td>
</tr>
<tr>
<td>c.350 BC</td>
<td>Atmospheric</td>
<td>Aristotle</td>
<td>Fiery atmospheric phenomena</td>
</tr>
<tr>
<td>c.350 BC</td>
<td>Atmospheric</td>
<td>Heracleides</td>
<td>Reflections from high clouds</td>
</tr>
<tr>
<td>c.330 BC</td>
<td>Atmospheric</td>
<td>Meteorus</td>
<td>Influx of Sun into clouds</td>
</tr>
<tr>
<td>c.330 BC</td>
<td>Celestial</td>
<td>Apollonius</td>
<td>Celestial bodies</td>
</tr>
<tr>
<td>c.300 BC</td>
<td>Celestial</td>
<td>Zero</td>
<td>Conjunctions of stars</td>
</tr>
<tr>
<td>c.290 BC</td>
<td>Celestial</td>
<td>Strato</td>
<td>Stars enveloped by cloud</td>
</tr>
<tr>
<td>c.130 BC</td>
<td>Atmospheric</td>
<td>Panaitius</td>
<td>False images of stars</td>
</tr>
<tr>
<td>c.100 BC</td>
<td>Atmospheric</td>
<td>Blichius</td>
<td>Violent, fiery winds</td>
</tr>
<tr>
<td>50 AD</td>
<td>Celestial</td>
<td>Seneca</td>
<td>Celestial bodies</td>
</tr>
</tbody>
</table>

Early Developments of Astronomy

Four broad phases can be identified:

1. Judicial Astrology (≈3000–1000 BC)
   - Events in sky self-evidently influence events on Earth.
   - Celestial ‘orders’ transmitted to Earth by sky-gods or deities.
     - A powerful ‘motive’ to observe the sky and interpret the celestial ‘omens’.
   - The sky gods are ‘announcing’ events on Earth, for example through the appearance of a bright comet or meteor, or by the fall of a meteorite or thunderbolt hurled by the sky-god Jupiter etc.

2. Zodiackal Astrology (≈1000–400 BC)
   - The slow transformation from Judicial Astrology to a growing focus on an important region of the sky associated with the principal sky-gods, i.e. the Zodiac.
   - The sky divided into sections, each with a different perceived ‘influence’ on people or events on Earth.

Later Developments of Astronomy

3. Horoscopical Astrology (≈400 BC to ≈1600 AD)
   - Based on the entirely false premise that wandering stars (‘planets’) exert a distant controlling influence on human affairs.
   - Provides an early example of a powerful, but ‘magical’ scientific concept, i.e. ‘action at a distance’.
   - Motivates careful observations of the planets: their paths against the fixed stars; their periods of revolution etc; all linked to predictions.
   - Demonstrates growing understanding and an increasingly ‘scientific’ approach to observers of the natural world.
   - Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.
   - Despite this, the idea of horoscope astrology has an enduring legacy — still believed by upwards of 25% of the population!

4. Scientific Astronomy (≈1600 AD to present)
   - New kind of astronomy, which ultimately proved to be an ‘inspiration of astronomy’ and its technical ‘spin-off’.

Ancient Greek Views: Anaximander’s Jets of Fire

1. Earth as a short, squat cylinder three times as wide as long, surrounded by air and floating freely at the centre of the observable Universe in an infinite space.

2. Sun, planets, stars are enclosed circular hoops of fire; they only become visible due to holes in their enclosing hoops, which allow the fiery substance to leak out and become visible. No direct evidence of his thoughts about comets; but note the hoops of fire lie below the Sun and Moon.

Why Astronomy?!

Three main strands of interest:

1. The broadly cosmological, ‘quasi-religious’ strand, going back thousands of years — the quest to understand our ‘Origins’, Man’s place in the Universe etc.

2. The ‘practical’ strand, i.e. the commercial, military, and economic ‘spin-off’ from astronomy, nowadays including education and the arts — e.g. the calendar; navigation; celestial mechanics; Earth observation; image processing; the ‘inspiration of astronomy’ and its technical ‘spin-off’.

3. The strand of pure science or ‘Astrophysics’ — the project to understand the nature, contents and interactions of all the objects in the entire Universe . . .

We live in a Golden Age, where the three strands have come together in a rare conjunction of activity: hence unprecedented advances in both observations and theory, the former almost always leading the latter.

Cradle of Civilization: Eastern View

Ancient Greek Views: Anaximander’s Jets of Fire

The sky divided into sections, each with a different perceived ‘influence’ on people or events on Earth.

The slow transformation from Judicial Astrology to a growing focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.

Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.

Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.

Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.

Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.

Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.

Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.

Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasional bright comet etc. ultimately proves to be a cul-de-sac for science.

Nevertheless, the focus on unimportant chance alignments of planets and stars, planetary conjunctions etc. (e.g. ‘Star of Bethlehem’), and on the ‘random’ appearance of an occasiona
Comets and Meteors as Omens or Prophecies

1. Precise astronomical observations were the key to prophecies; and the omen literature always took the form: “If [astronomical observation] then [terrestrial effect].” E.g., quoted by Bjorkman (Meteoritics, 8, 91, 1973): “If a shooting star flashes as bright as a light or as a torch from east to west and disappears on the horizon, then the army of the enemy will be slain in its onslaught.”

2. Some early cometary observations are quoted by Olivier (in “Comets”, 1930).

What could have led to these ideas? Seneca (c.4 BC – 65 AD) gives some insight. Referring to the “difference” between us Romans and Etruscans, he remarks, “... We believe that lightning is caused by clouds colliding, whereas they believe that clouds collide in order to create lightning. Since they attribute everything to the gods, they are led to believe not that events have a meaning because they have happened, but that they happen in order to express a meaning.”

Cradle of Civilization: Atlantic View

Rock Art at Knockmany Chambered Tomb, Co. Tyrone

View of Knockmany in Nineteenth Century

Rock Art and Megalith in Scotland

Further Examples of Rock Art in UK and Ireland

Commonly Occurring Motifs in British Rock Art

Chinese/Greek/Roman Classification of Comets
Comet Images from Fifteenth to Nineteenth Century

Great Comet of 1910: Drawing versus Photograph

Comets of 1577 and 1995 Hale-Bopp (Two Prints)

17th and 19th-Century Views of Halley’s Comet

Impacts Occur: 20th Century Examples

Effects of Impacts: Great and Small

Short-Term Implications — I

Ancient societies appear to be obsessed by the sky:

- e.g. early astronomical interest in ‘the sky’, evidence of megalithic monuments/prehistoric ‘rock art’.
- Neugebauer: “… ancient ‘astrology’ can be much better compared with weather prediction from phenomena observed in the sky than with astrology in the modern sense of the word.” Suggests knowledge of direct link between sky and Earth.

Suggests that some solar-system phenomena may change on much shorter time-scales than we normally consider possible.

Short-Term Implications — II

Ancient Greek “mysteries”: Problem of Milky Way … Zodiacal Light?

- Anaximander: describes stars as little jets of gas spouting out of a punctured hoop of fire.
- Aristotle: believes the Milky Way to lie in the sublunary zone, a hot accumulation of the disintegration products of many comets.
- Anaximander, Parmenides, Leucipus: the ‘stars’ lie below the Sun and the Moon.
- Metrodorus and Oenopides of Chios: the Milky Way is the former path of the Sun.
- Anaximander and Democritus: the Milky Way lies in the shadow of the Earth.

Image of Milky Way (A. White); Leonid meteor storm; and zodiacal light.
Table of Cometary Theories from c.1600–1800

<table>
<thead>
<tr>
<th>Theory and Broad Type</th>
<th>Originator and Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comets are exhalations from planets: a <code>halfway house</code> between the <code>celestial</code> and <code>atmospheric</code> theories</td>
<td>Tycho (c.1600)</td>
</tr>
<tr>
<td>Comets are interstellar objects; move on rectilinear paths and populate the <code>heavens</code> in great numbers; form from the celestial fires by processes akin to cloud formation</td>
<td>Kepler (c.1600)</td>
</tr>
<tr>
<td>Comets are attached to planetary motions; ejected by violent whirlwinds into parabolic orbits</td>
<td>Galileo (c.1600)</td>
</tr>
<tr>
<td>Comets are celestial objects; orbits elongated ellipses</td>
<td>Sir William Lower and Henry Percy (c.1610)</td>
</tr>
<tr>
<td>Comets are exhalations from the Sun: the cindery refuse from great solar conflagrations</td>
<td>Anon. (c.1620)</td>
</tr>
<tr>
<td>Comets are vapours that condensed in planetary atmospheres; ejected by violent whirlwinds into parabolic orbits</td>
<td>Hevelius (c.1680)</td>
</tr>
<tr>
<td>Comets are interstellar objects: vapours ejected from stars</td>
<td>Cassini (c.1680)</td>
</tr>
<tr>
<td>Comets are gravitating solar-system objects; akin to planets</td>
<td>Halley/Newton (c.1680)</td>
</tr>
<tr>
<td>Comets akin to planets; formed as part of solar system through collision of a comet with the Sun</td>
<td>Buffon (c.1745)</td>
</tr>
<tr>
<td>Comets, like planets, form by condensation in protosolar nebulae, comets akin to planets</td>
<td>Kant (c.1755)</td>
</tr>
</tbody>
</table>

Initial Conclusions —— Drawn from History

1. Comets can be the most prominent objects in sky, as bright as the brightest stars. Appear unpredictably, but move like planets . . .
2. Observations go back thousands of years, when comets and associated meteoric phenomena were scrutinized as `omens` for events on Earth. Provide insights into early cosmologies and ideas about the sky.
3. Mankind's puzzling `fear` of comets never adequately explained. Evidence suggests `the sky` may have been significantly different in proto-historic times.
4. Two thousand years of `atmospheric` ideas about comets finally superseded during the 1600s by the `celestial` hypothesis. Subsequent debates focus on `interstellar` versus `solar system` ideas.
Early 'Planetary' versus 'Interstellar' Arguments

Increasing data set plus translations of historic (mostly Chinese) records meant that comets became definitely established as celestial objects; but are they solar system or interstellar in origin?

1. Most comets have parabolic orbits—quite different in shape and inclination from the planets.
2. The few known ‘periodic’ orbits (e.g. Halley’s Comet) were and were—questioned, e.g.
   - how far did Newton’s new law of gravity (‘action at a distance’) extend?
   - how sure can we be that two comets with similar orbital elements are the same comet or, coincidentally, two separate comets?
3. Return of Halley’s comet in 1759, as predicted, a significant advance.
4. But appearance of Lexell’s comet (1770) proved the matter was not clear-cut.
   - Orbit definitely elliptical, but object previously ‘captured’ and then ‘ejected’ by Jupiter.

Laplace’s ‘Nebular Hypothesis’: Interstellar Comets

By early nineteenth century, the 2,000-year long debate ‘atmospheric vs. celestial’ finally settled in favour of celestial theory, with comets as ‘gravitating’ bodies...

- But are comets truly ‘solar system’ or ‘interstellar’ objects?
- Laplace’s Nebular Hypothesis (1805): Developed independently of Kant’s (1755) theory; the central dominance of the Sun; the planetary orbits being nearly circular and coplanar etc.

1. Provides a physical model based on Newtonian principles and collapse of contraction of initially slowly rotating promordial gas cloud:
   - Contraction leads to ‘spin-up’ and shedding of rings of gas from the central body’s equator — leading to formation of the observed planets.
   - Most of the mass remains at the centre — leading to the Sun.
2. But comets remain an anomaly — and therefore must have a separate ‘interstellar’ origin...

NB: Kant (1755) had developed a different nebular theory, but had thought that comets could be incorporated in the model.

Lexell’s Comet: Complex Dynamical Evolution

1. Discovered by Messier on 14/15 June 1770; soon recognized as having an unusually large daily motion;
2. Exceptionally close approach to Earth (ΔE = 00146 AU) on 1st July 1770, the closest approach of any comet to Earth in recent times;
3. First comet to have mass estimated (< 1/5000 M☉).
4. First comet to have elliptical orbit determined from observations of just one revolution, i.e. a = 31.5 AU, q = 0.67 AU, P = 5.6 yr = 0.5P⊙ — but comet never seen again!
5. Later calculations show comet had an original orbit with q = 2.9 AU and P = 9.2 yr. Exceptional close approach to Jupiter (ΔJ = 0.02 AU, on 27 March 1797) led to observed Earth-crossing orbit destined to pass just 2 Jovian radii above Jupiter (ΔJ = 0.002 AU, on 2 July 1779), which drastically changed orbit again;
6. New orbit has perihelion near Jupiter (q = 5.17 AU) and semi-major axis a = 41.0 AU, i.e. P = 280 yr. Illustrates complexity of cometary dynamical evolution.

Laplace (1805) versus Lagrange (1814)

1. Discovery of first asteroids: Ceres and Pallas, by Piazzi and Olbers in 1801 and 1802 respectively.
   - Ceres originally described by Piazzi as a ‘star-like’ comet;
   - Early suggestions of transient nebulosity around both objects (Herschel, Schröter); confirmation elusive;
2. The new objects (‘asteroids’) upset underlying simplicity of Laplace’s nebular hypothesis: proving there exist minor ‘planets’ in relatively high-inclination, non-circular orbits.
   - Olbers speculates they might be fragments of a former much larger planet between Mars and Jupiter — blown to pieces by internal forces, or the impact of a comet ...
3. Thus a new ‘solar system’ theory introduced, harking back to earlier ‘planetary’ and catastrophic notions about comets.
4. Lagrange (1814) posthumously publishes proposal that at least some comets might have such an origin.

A Key Observation: The Solar Motion

1. Interstellar theory depended on Sun essentially at rest with respect to assumed interstellar population;
2. Herschel (1783) previously concluded Sun was moving, but results not statistically significant (e.g. Bisell, Bessel); Gauss (1815) nevertheless highlights its potential importance for comets;
3. Argelander (1837) demonstrates reality of solar motion; but by then its implications for comets ‘forgotten’; Laplace’s ‘interstellar’ theory survives.
4. Carrington (1860, 1863) emphasizes that solar motion would produce more comets coming from one direction than another (cf. aberration).
   - But cannot see any effect — and concludes solar motion is wrong!
5. Poinsot (1846) and Schiaparelli (1869) put argument right away around, but not accepted: e.g. Newton (1878): ‘Professor Schiaparelli by introducing (improperly, as I am sure he will concede) the motion of the Sun in space was led to decide against a foreign origin for comets.’
6. Fabry (1893) finally overturns Laplacian paradigm: concludes Sun surrounded by comoving comet cloud; hence comets are ‘Solar System’ objects.

New Discoveries c.1800–1900

1. Rapid increase in comets with ‘known’ mostly parabolic orbits.
2. Whereas in 1790 there were 78 parabolic comets (including 7 sightings of Halley’s comet); by 1890 there were c.270, of which 26 were definitely periodic and 43 definitely elliptical.
3. Leads to growing focus on the ‘periodic’ subsample: comets with mostly low-inclination, ‘direct’ orbits and greater orbital similarity to asteroids than to other comets.
4. Suggests ‘planetary’ solar system source for these short-period, low-inclination comets.

Formation of Solar System Following Nebular Hypothesis

Illustration of origin of solar system according to Laplace’s Nebular Hypothesis, after Whipple (1964)


Illustration: STFC Summer School 2010 September 10 – p.33
Laplace Rejected: A ‘New’ Solar System Paradigm c.1900

1. Number of short-period comets a growing problem for ‘capture’ hypothesis.
2. If so, then short-period comets perhaps formed — like asteroids — in a ‘planetary disruption’ event (cf. Lagrange 1814, Proctor 1870); or by break-up of a large comet (Alexander 1850, Bredichin 1889) . . .
   - In any case, short-period comets must have ‘solar system’ origin. And if so — Somehow with the comets with ‘parabolic’ orbits.
3. Laplace’s ‘interstellar’ theory therefore rejected; leads to a return to Kant’s ‘solar nebula’ picture.
4. Two new themes at this time: (1) if comets are ‘solar system’ in origin, then what do comets tell us about origin of solar system?; and (2) the observed orbits are probably not those that originally prevailed.

Theory now suggest observed orbits are example of Darwinian evolution. Parabolic excess an example of Darwinian ‘survival of the fittest’ — originating from an initial primordial population containing all possible orbits.

Paths Leading to Oort Cloud c.1920–1950

1. New age for Earth around 1920 (billions of years rather than tens or hundreds) highlights survival problem for parabolic comets.
   - The ‘Darwinian’ argument now implies we should see no comets at all!
   - And ‘capture’ theory still fails to explain number of short-period comets.
2. Still, most astronomers remain irrationally attached to ‘solar system’ model.
3. A few develop alternative ‘interstellar’ theories, e.g. (1) recent ‘capture’ of comets by passage of Sun through a dense ‘interstellar cloud’ of comets (Nöike 1909, Bobrovnikoff 1929); and (2) comets formed by passage of Sun through a dense interstellar dust cloud (Lytleton 1948).
4. Öpik (1932) notes Darwinian argument depends on comets always being subject to decay.
   - The first quantitative theory of stellar perturbations on long-period orbits. Shows cometary perihelia evolve outwards (and inwards) under stellar action; the seed for ‘Oort cloud’ picture.

Nineteenth and Early Twentieth-Century Theories

 Originator and Date
<table>
<thead>
<tr>
<th>Theorist</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laplace (c.1805)</td>
<td></td>
</tr>
<tr>
<td>Lagrange/Brunet (c.1810)</td>
<td></td>
</tr>
<tr>
<td>Peirce (1849)</td>
<td></td>
</tr>
<tr>
<td>Schiaparelli (c.1860)</td>
<td></td>
</tr>
<tr>
<td>Proctor (1884)</td>
<td></td>
</tr>
<tr>
<td>Newcomb (c.1910)</td>
<td></td>
</tr>
<tr>
<td>Chamberlin/Crommelin (c.1920)</td>
<td></td>
</tr>
<tr>
<td>Bobrovnikoff (1929)</td>
<td></td>
</tr>
<tr>
<td>Vuskovac (1930–1940)</td>
<td></td>
</tr>
<tr>
<td>Öpik (1932)</td>
<td></td>
</tr>
<tr>
<td>Nöike (1936)</td>
<td></td>
</tr>
</tbody>
</table>

Theory and Broad Type
- Comets are interstellar objects
- Comets are result of planetary explosion
- Comets are solar system objects, originating at great heliocentric distances
- Comets are solar system bodies, occupying a huge co-moving swarm about the Sun
- Comets are formed in vast planetary explosions
- Comets originate in the collapsing protosolar nebula
- Comets originate in the collapsing protosolar nebula
- Comets originate in the collapsing protosolar nebula
- Comets are ‘survivor’ of high order planets
- Comets are primordial solar system bodies; LP orbits affected by stellar perturbations
- Comets are interstellar; recently captured via interaction with dense resisting medium

Improved Statistics c.1920–1950: LP and SP Comets

<table>
<thead>
<tr>
<th>Range 1/a</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000–0.002</td>
<td>177.0</td>
</tr>
<tr>
<td>0.002–0.004</td>
<td>10.0</td>
</tr>
<tr>
<td>0.004–0.006</td>
<td>8.0</td>
</tr>
<tr>
<td>0.006–0.008</td>
<td>7.0</td>
</tr>
<tr>
<td>0.008–0.010</td>
<td>2.5</td>
</tr>
<tr>
<td>0.010–0.012</td>
<td>6.5</td>
</tr>
<tr>
<td>0.012–0.014</td>
<td>1.0</td>
</tr>
<tr>
<td>&gt; 0.014</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Left: Near-isotropic distribution of LP cometary inclinations (589 LP comets up to 1982).
Right: Distribution of SP comet aphelia Q correlating with planetary semi-major axes (121 periodic comets up to 1982).

Progress in Calculating Planetary Perturbations

1. Observed orbits not the original orbits.
2. Planetary perturbations change mostly the orbital energy $E$ per unit mass, i.e. lead to $\Delta E = - (GM_m/2a) \Delta (1/a)$.
3. For randomly distributed close encounters (i.e. strong perturbations), probability of energy change $\Delta E \propto a^{-1/3}$ (for encounters with Jupiter):
   $$p(a) \Delta a \approx \frac{8}{3} \left( \frac{M_j}{M_\odot} \right)^2 \frac{1}{a^{1/3}} \Delta a$$
4. Leads to concept of ‘capture probability’, $p_c$ (cf. Lesse). i.e. probability to evolve in one revolution to semi-major axis less than $a$:
   $$p_c(a) \approx \frac{4}{3} \left( \frac{M_j}{M_\odot} \right)^2 \frac{1}{a^{1/3}}$$
5. Capture probability to period $P < 200$ yr is $\lesssim 5 \times 10^{-5}$; emphasizes problem of observed number of observed short-period orbits.

Cometary 1/a-Distribution: Early Diffusion Theory

1. Changes in $x = 1/a$ akin to random walk in $E$.
2. Define $p_x = r.m.s. \Delta (1/a)$ per revolution.
   $$\Rightarrow$$ after $N$ revolutions, expect $x \approx \sqrt{N}p_x$, i.e. $\approx 10^3$ revolutions to reach $P < 200$ yr.
3. Solve diffusion equation (ignoring decay):
   $$\frac{\partial p}{\partial t} = \frac{\partial^2 p}{\partial (x^2)}$$
   where $P(a) = 2\pi (GM_\odot)^{-1/2} x^{3/2}$
4. Leads to:
   $$p(x, t) = \left[ 1 + \left( \frac{x}{b_0} \right) \right] e^{-b_0/t}$$
   where $b_0 = 8 \sqrt{\pi P(x)/a_x^2}$.
5. i.e. diffusion time-scale $\lesssim 1$ Myr.
   $$\Rightarrow$$ rapid evolution to a quasi-steady state distribution . . .

Solution of Diffusion Equation

- $p_x$ distribution versus $q$ (AU$^{-1}$) for randomly distributed initial parabolic orbits. Very roughly, $p_x(q) \approx 10^{-3} \exp(-q/2.4)$ AU$^{-1}$.
- Solution of diffusion equation with no decay (after Van Woerkom 1948); note rapid evolution to ‘flat’ distribution, completely contrary to observed 1/a-distribution (histogram).

Lytleton’s (1948) Accretion Theory

1. A novel variant of the interstellar hypothesis; the first to address both where comets come from and how they are formed.
2. Consider motion of Sun through a dense dust cloud of density $\rho_{dust}$. Collisions of dust grains on axis of symmetry dissipate energy and cause some grains to be captured — those coalesce to become proto-comets.
3. Get inflow within a stagnation radius $R_0 \approx GM_\odot/V_c^2$. For $V_c = 5$ km s$^{-1}$, $R_0 \approx 35$ AU.
4. In a steady-state, the stream mass per unit length is $\dot{M} \approx 2\pi R_0 \rho_{dust} R_0^2$ and the stream velocity $V_c$ is roughly the free-fall speed from $R_0$. Thus, any new comets have initial semi-major axes $a \lesssim R_0/2$. 
**Problems with Lyttleton’s Theory**

1. Dust clouds do not exist on their own. The interstellar dust is dominated (by a mass fraction of at least a factor of 50) by hydrogen gas. Effects of gas must be included; this never done.
2. The supposed proto-comets are far too small. Even if an accretion stream could be set up, only very short segments of length \(d(r) \leq 2, \text{AU}/c^2\) at heliocentric distance \(r\) could successfully contract against the tidal field of the Sun. This leads to \(m_c \leq 10^{2} (10 \text{ km}^{-1} / V/r)^4 H_m / (10^{-22} \text{ kg m}^{-3})^{-1/2} \text{ kg}\).
3. Initial orbits too short period and too anisotropic. Lyttleton argues for a long period of randomisation of orbits following the last accretion episode, but then the predicted 1/\(a\)-distribution quite wrong (diffusion theory).
4. The supposed proto-comets are on initial orbits directed towards Sun (or solar-system barycentre). Unless inhomogeneities or planetary perturbations are invoked to deflect the stream, all the initial comets will fall onto the Sun.

In summary, despite strong advocacy of theory by Lyttleton for next 30 years: “The theory is disproved: an honourable fate for a good theory”!

---

**Birth of a Theory: The 1950 Oort Cloud**

1. Oort considers the original 1/\(a\)-values of the 19 most accurate orbits; i.e. those with mean errors < \(10^{-4} \text{ AU}^{-1}\).
2. Enables fine-grained binning of 1/\(a\)-distribution for first time.
3. More than half had ‘original’ 1/\(a\)-values < \(5 \times 10^{-8} \text{ AU}^{-1}\), and none had 1/\(a\) > \(750 \times 10^{-7} \text{ AU}^{-1}\).
4. Note the extreme narrowness of the sharp peak in the distribution of ‘observed’ original 1/\(a\)-values.

---

**Comparison with Modern Data**

- Histogram of original 1/\(a\)-volume (left): cone-like distribution from Lyttleton (1948); flat distribution from modern data.
- Histogram of observed 1/\(a\)-volume (right): cone distribution from Lyttleton (1948); flat distribution from modern data.

---

**Argument for Oort Cloud — In Modern Terms**

1. **Observations**
   - We see \(~1\) ‘new’ comet \((q < 5 \text{ AU}, H_{10} < 7)\) discovered per year.
   - Semi-major axes \(a \geq 2 \times 10^4 \text{ AU}\), near the parabolic limit; orbital periods \(P \sim 3-30 \text{Myr}\) — short compared to age of solar system.
   - These ‘new’ comets strongly perturbed by Jupiter, so that \(-50\%\) ejected, the remainder ‘captured’.
   - ‘Captured’ comets return, to be ejected or lost to short-orbit comets and eventual decay.

2. **Conclude:** All observed comets are ultimately lost; and the ‘loss cone’ affects all orbits with \(q \leq 15 \text{ AU}\); and the loss timescale < age of solar system.
3. ‘Comets are either a transient phenomenon, or there is a long-lived reservoir to replenish those that are lost.
4. Oort adopts primordial ‘steady-state’ hypothesis.

---

**View of Oort Cloud**

1. Like a globular star cluster, such as M13...
   - Imagine Sun at centre
   - The stars become ‘comets’
   - The shape (like a flattened rugby ball) is about right
   - The strong concentration of comets towards the centre is about right
   - The overall dynamics is similar
2. Can calculate ‘families’ of Oort cloud models, in the same way as for star clusters and galaxies.
3. External perturbations (e.g. stars) change cometary orbits

---

**Argument for Oort Cloud — c.1950**

1. Sharp spoke in observed 1/\(a\)-distribution rules out interstellar capture (Van Woerkom 1948). Lyttleton’s ‘capture theory’ (1948) seriously deficient...suggests comets have primordial solar system origin, and the observed comets are coming into inner planetary region for the first time.
2. If comets are primordial, there must be a ‘comet store’ — the ‘home’ of the comet — somewhere beyond the zone of visibility, where comets can survive. Logically, this must contain comets in orbits of large perihelion distance.
3. Oort then addresses how to get comets from safe storage into inner solar system:
   - Planetary perturbations? — NO: they broaden the 1/\(a\)-distribution too much (van Woerkom).
   - Resistance of dense interstellar medium? — NO: it is implausible, and such a medium would primarily affect the comets’ aphelion distances, again contradicting the observed 1/\(a\)-distribution.
   - Stellar perturbations? — YES: cometary orbits extend up to halfway to the nearest star; they must be affected by passing stars (cf. Opik 1932).

---

**Modern Argument (cont.)**

1. ‘New’ comets are only lost if \(q \leq \text{less than} \text{ cone}\), i.e. \(q \leq 15 \text{ AU}\):
   - Oort’s reservoir must contain long-period comets of large \(q\).
2. For long-period orbits, planets change the orbital energy, \(\Delta 1/a\), keeping \(q\) nearly constant; stars change the angular momentum, \(\Delta q\), keeping \(1/a\) constant.
3. In other words, stellar perturbations change \(q\).
   - \(\Delta q\) per revolution is about the size of the loss cone, provided the orbit is large enough.
   - The reservoir must contain comets of very long orbital period \(a > 2 \times 10^4 \text{ AU} \), \(P > 5 \text{ Myr}\) — just like the observations.
   - Leads to Oort’s idea of a nearly spherical cloud of comets with orbits extending up to halfway to the nearest star.
4. The cloud is ‘gardened’ by external perturbations.
   - Including stellar, molecular cloud and large-scale systematic effects of Galactic tide.

---

**Standard (1950) Model**

1. Assume: (1) spherical symmetry; outer radius \(R_o \sim 200,000 \text{ AU}\); (2) random velocities, ‘gardened’ by stellar perturbations; (3) hydrostatic equilibrium (cloud neither expanding nor contracting); and (4) a simple energy distribution equation, e.g. a power-law distribution of orbital energies per unit mass \(E \sim GM_o/r^2\).
2. If \(f(E) \propto |E|^{-3} \text{ d}E\), then the number density \(n(r)\) is roughly proportional to \(r^{-4}\).
3. Oort’s (1950) model has \(\gamma = 5/2\), corresponding to velocity space being uniformly filled at \(r = 1\) up to a value \(V_{\text{max}}\) equal to the free-fall speed from \(R_o\) to \(r\). This implies \(n(r) \propto r^{-1}\), i.e. most of the mass near the outer edge.
4. Other models have smaller \(\gamma\) (e.g. \(\gamma = 3\)), and much sharper inward density increases. The structure is much more like a dense star cluster, with a strong concentration of mass towards the centre, not a shell.
5. Leads to the concept of the Oort cloud Dense Inner Core, a region containing most of the cometary mass, and relatively safe from external perturbations.
**Evolution and Survival**

1. Two main types of external perturber: stars and molecular clouds.
   - Galactic tide also drives comets into inner solar system, but has little direct effect on Oort cloud’s disruption.
2. Stars pass through and beyond the Oort cloud, causing gradual unbinding of cometary orbits; the 'stellar' half-life is \( t_{2:1} = 2 \times 10^5 (2 \times 10^4) \text{AU} / a \text{yr} \).
3. Molecular cloud pass beyond the Oort cloud, but are much more massive than stars; the 'molecular cloud' half-life is \( t_{2:1} = 2 \times 10^5 (2 \times 10^4) \text{AU} / a \text{yr} \).

\[ \Rightarrow \text{standard Oort cloud dynamically unstable beyond} \ a \approx 2 \times 10^4 \text{AU over age of solar system; it must be replenished from within: the Dense Inner Core.} \]

---

**Variable Oort Cloud Flux**

2. Comet flux roughly proportional to mass-density, \( \rho \) from Oort cloud. \( \Delta \)Comet flux dominates Galactic tide (see Figure, after J. Matase et al. 1995).
3. \( \Delta \rho \) per revolution depends on \( a \), and Galactic latitude of perihelion, \( b \), i.e.

\[ \Delta \rho \propto (10b^2 \sqrt{2/M_\odot}) \sin(2b) q^{1/2}a^{3/2} \]

---

**Fading Problem: Where Are the ‘Dead’ Comets?**

1. Observed new-comet flux: Approximately 1 comet per year brighter than \( H_{20} = 7 \) (corresponds to diameter \( d \gtrsim 5 \text{ km} \)) with \( q < 5 \text{ AU} \), i.e. with perihelion distance within Jupiter’s orbit.
2. Capture probability to 'Halley-type comet' (HTC), i.e. capture probability to \( P \lesssim 10^{-2} \) yr, \( p_c \approx 0.01 \) per new comet; the rest get ejected.
3. Mean dynamical lifetime as a Halley-type comet: \( t_{\text{Dyn}} \approx 3 \times 10^7 \text{ yr} \).
4. \( \approx \) steady-state number of HTCs, \( N_{\text{HTC}} \), given by \( N_{\text{HTC}} \approx 1.0 \times 10^2 \times 300 \approx 3000 \).
5. Greater than 100 times more than observed: where are the dead comets?!
   - Perhaps 'dark HT asteroids', 'boulders', or 'dust'?!

---

**Mean Energy Transfer Rate**

1. Change in orbital energy in a single encounter can be shown to be of the order of \( \Delta E \approx 5 (a/3 \times 10^4 \text{AU})^{1/2} (q/1 \text{AU})^{1/2} \text{ AU} \)

---

**Physical of External Perturbations**

1. Consider a perturber of mass \( M \) passing Sun with velocity \( V \) and impact parameter \( b \) with respect to Sun and \( d \) with respect to a comet at heliocentric distance \( r \).
2. Then the relative velocity change of the comet with respect to the Sun is the difference of the two impulses, i.e.

\[ \Delta v = \frac{2GM}{BV} \frac{2GM}{BV} b - \frac{2GM}{BV} \left( \left( \frac{b'}{\rho} \right) - 1 \right) b \frac{mb}{\rho} \left[ - (I \cdot \dot{V}) \right] \]

---

**Heuristic Results**

1. Mean relative velocity change in a single encounter is approximately:

\[ \Delta v = \frac{2GM}{BV} \left\{ \sqrt{2} \ b < \sqrt{12}a \right\} \frac{\sqrt{\rho}}{\sqrt{\rho}} \frac{\sqrt{\rho}}{\sqrt{\rho}} b > \sqrt{12}a \]

2. On short timescales (e.g. \( t \lesssim 30 \text{ Myr} \)), the closest stellar encounter expected during a given time interval \( t \) has impact parameter \( b_{\text{Min}} \approx 2(2nV)\tau^{-1/2} \), where \( n \) is the number density of perturbers. For stars this usually implies \( b \geq a \), which leads to \( \Delta v_{\text{Max}} \approx 4(\tau/7)^{1/2} \text{ AU} \).

3. This leads to \( \Delta v_{\text{Max}} \approx 4(\tau/7)^{1/2} \text{ AU} \), where \( \rho = m \text{M} \approx 0.05 \text{ M}_\odot \text{pc}^{-3} \) for stars is the mass density of perturbers.
4. Finally, setting \( t = \tau(2\pi/a) \approx 5.2 (a/3 \times 10^4 \text{AU})^{1/2} \text{Myr} \), the maximum change in perihelion distance during a single revolution can be shown to be of the order of \( \Delta P \approx 5 (a/3 \times 10^4 \text{AU})^{1/2} (q/1 \text{AU})^{1/2} \text{AU} \)}

---

**Long-Term Evolution**

1. 1950 Model: quasi-steady state; comets in long-term 'deep freeze' of Oort cloud; stars dominate the evolution; no dense inner core.
2. Modern view:
   - Short timescales: \( t \lesssim 10 \text{ Myr} \): \( \Delta E \) dominated by Galactic tide and passing stars; quasi-steady-long period comet flux; \( \Delta E \) dominated by stars.
   - Medium timescales: \( 10^3 \lesssim t \lesssim 500 \text{ Myr} \): periodic new-comet flux due to Sun's orbit about Galactic plane; rare, close stellar passages more important in randomizing orbits; \( \Delta E \) still dominated by stars.
   - Long timescales: \( 500 \lesssim t \lesssim 4000 \text{ Myr} \): rare, close molecular cloud encounters disrupt outer cloud, dominating \( \Delta E \); there, rare, close stellar encounters stir up inner core.

Together, these replenish transition zone between inner and outer Oort cloud and stir up orbits in Dense Inner Core.

---

**Fading Problem: First Recall 1/a-distribution**

1. \( \text{Comet flux at} \ 1/a \text{distribution plot} \)
2. \( \text{Histogram of original} \ 1/a \text{values, the comet flux} \)
3. \( \text{Galactic tide} \: \text{the comet flux} \)

---

**Mean Fading Rate**

1. \( \text{Mean Fading Rate} \: \text{the comet flux} \)
2. \( \text{Long-term evolution} \: \text{the comet flux} \)

---

**Physics of External Perturbations**

1. Consider a perturber of mass \( M \) passing Sun with velocity \( V \) and impact parameter \( b \) with respect to Sun and \( d \) with respect to a comet at heliocentric distance \( r \).
2. Then the relative velocity change of the comet with respect to the Sun is the difference of the two impulses, i.e.

\[ \Delta v = \frac{2GM}{BV} \frac{2GM}{BV} b - \frac{2GM}{BV} \left( \left( \frac{b'}{\rho} \right) - 1 \right) b \frac{mb}{\rho} \left[ - (I \cdot \dot{V}) \right] \]

---

**Mean Energy Transfer Rate**

1. \( \text{Mean Energy Transfer Rate} \: \text{the comet flux} \)
2. \( \text{Cometary orbital energies thus diffuse and systematically increase (i.e. become less tightly bound) owing to external perturbations.} \)
3. \( \text{Approximate result for point-mass perturbers:} \)
4. \( \text{define} \: a_v = \sqrt{2c^2/\rho_{\text{Min}}} \), \( \text{where} \: \rho_{\text{Min}} \approx 2(2nV)\tau^{-1/2} \text{AU} \), \text{is the most probable minimum impact parameter for the perturbers of number density} \: n \), \text{then the mean energy transfer rate can be shown to be approximately}

\[ \dot{\epsilon} = \frac{4\pi G^2 M^2 n}{V} \left\{ \frac{(a/2)}{a_v}^2 \left( 2\ln(2/a_v) + 1 \right) a < a_v \right\} \]

---

**Mean Energy Transfer Rate**

1. \( \text{Mean Energy Transfer Rate} \: \text{the comet flux} \)
2. \( \text{Cometary orbital energies thus diffuse and systematically increase (i.e. become less tightly bound) owing to external perturbations.} \)
3. \( \text{Approximate result for point-mass perturbers:} \)
4. \( \text{define} \: a_v = \sqrt{2c^2/\rho_{\text{Min}}} \), \( \text{where} \: \rho_{\text{Min}} \approx 2(2nV)\tau^{-1/2} \text{AU} \), \text{is the most probable minimum impact parameter for the perturbers of number density} \: n \), \text{then the mean energy transfer rate can be shown to be approximately}

\[ \dot{\epsilon} = \frac{4\pi G^2 M^2 n}{V} \left\{ \frac{(a/2)}{a_v}^2 \left( 2\ln(2/a_v) + 1 \right) a < a_v \right\} \]
Oort Cloud Survival Problem

1. For stars and $t \approx 4.5$ Gyr, we have $a \gg a_c$. This implies $\dot{a} \approx \text{const.}$
2. For molecular clouds and $t \approx 4.5$ Gyr, we have $a \ll a_c$, i.e. $\dot{a} \approx \text{const.}$
3. The net result is:

$$t = \frac{1}{4.752} \frac{GM}{\dot{a}^2} \approx 2 \times 10^3 \left(\frac{2 \times 10^4 \text{AU}}{a_c}\right) \text{yr}$$

and

$$t = \frac{1}{8.199} \frac{GM}{\dot{a}^2} \approx 2 \times 10^3 \left(\frac{2 \times 10^4 \text{AU}}{a_c}\right)^3 \text{yr}$$

5. Thus, due to both clouds and stars, the majority of comets with initial $a \approx 2 \times 10^5$ AU will be lost. This is the Oort cloud survival problem.

Conclusions — Issues of Current Concern

1. Ancient history suggests ‘the sky’ may have been significantly different in proto-historic times (e.g. more ‘active’, more interplanetary debris, brighter zodiacal light etc.); how can that be?
2. Cometary masses range up to the size of dwarf planets; what are the effects of occasional ‘giants’ on Earth?
3. Total mass of Oort cloud may be very large ($\approx 10^9 M_{\odot}$ pc$^{-1}$); implies potentially serious difficulties for ‘standard’ primordial solar system picture?
4. ‘Fading problem’ still not understood, but effectively determines the predicted $\dot{n}/n$-distribution; what happens to cometary debris?
5. Meteoroid streams initially very fine-grained; leads to strong time-dependence in accretion of dust and small bodies on Earth.

Conclusions — General Points

1. ‘Comets’ can sometimes be the most prominent objects in sky; their study goes back thousands of years.
2. Comets touch on many areas of astronomy, not least solar-system science; they have had a significant impact on the Earth and on the development of scientific ideas.
3. Earth an ‘open’ system, in touch with its near-space celestial environment: a paradigm shift as significant as Copernicanism.
4. Solar system ‘very leaky’; interesting implications for the dust, small bodies and planets in molecular clouds and the interstellar medium; what about comet clouds around other stars?
5. Modern picture of comets; a balance between the historical catastrophist and Newtonian uniformitarian views; comets as potential destroyers of life and as objects that bring the necessities of life (e.g. water, organics, perhaps seeds of life itself) to Earth.

Acknowledgements

Astronomy at Armagh Observatory is funded by the Northern Ireland Department of Culture, Arts and Leisure.