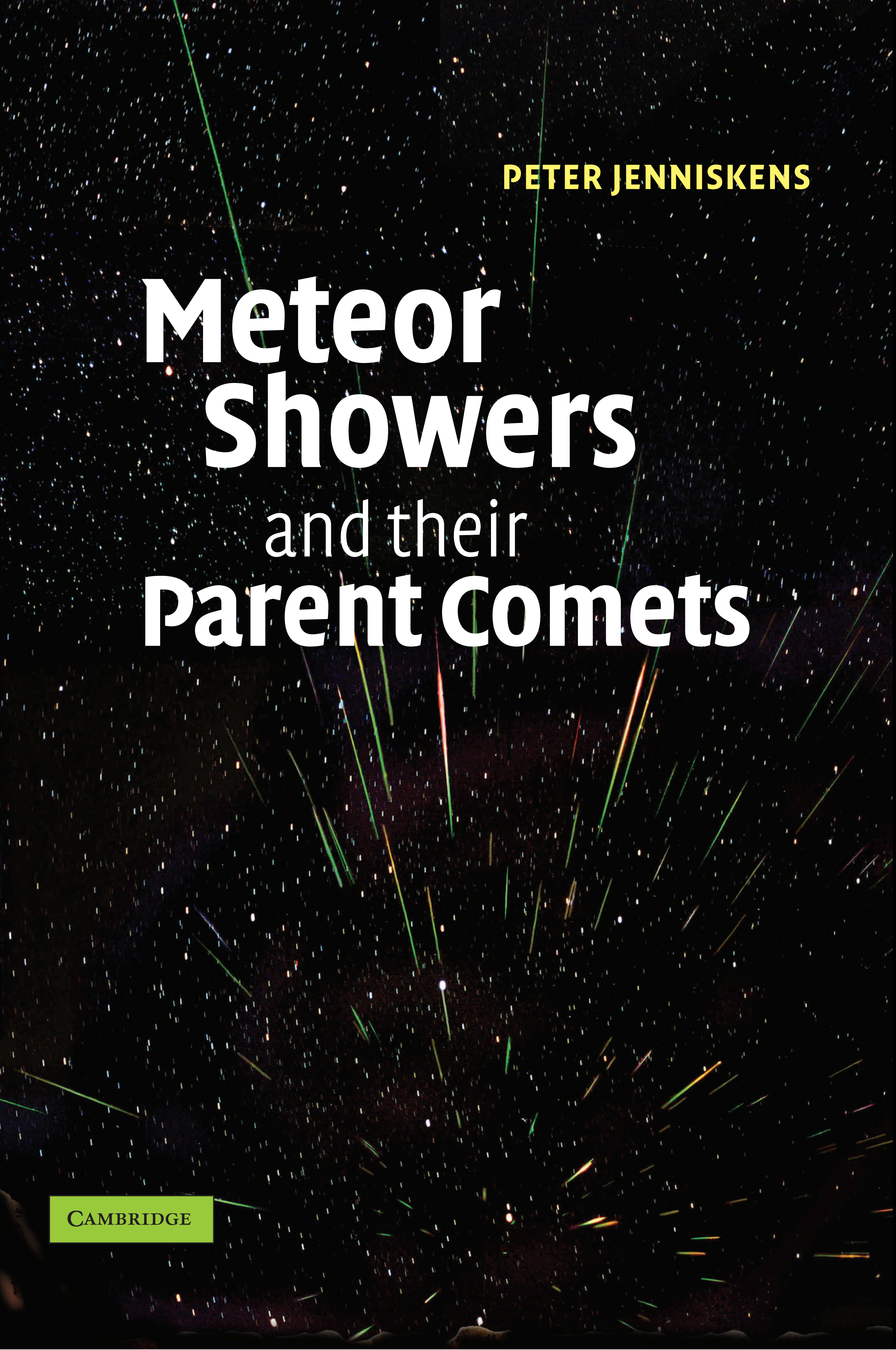

PETER JENNISKENS

Meteor Showers and their Parent Comets

CAMBRIDGE

Meteor Showers and Their Parent Comets

It is only in the past ten years that advanced computing techniques and painstaking observations have enabled the successful prediction and observation of meteor storms. Spectacular displays of "shooting stars" are created when the Earth crosses a meteoroid stream, causing the meteoroids to light up into meteors as they enter our atmosphere.

Meteor Showers and Their Parent Comets is a unique handbook for astronomers interested in observing meteor storms and outbursts. The author, a leading astronomer in the field and an active meteor storm chaser, explains how meteoroid streams originate from the decay of comets (and asteroids) and how they evolve into ever changing orbits by the gravitational pull of planets to cause meteor showers on Earth. He includes the findings of recent space missions that have visited comets and asteroids, the risk of meteoroid impacts on Earth, what showers to expect on other planets, and how meteor showers may have seeded the Earth with the ingredients that made life possible.

All known meteor showers are identified, accompanied by fascinating details on the most important showers and their parent comets. The book predicts when exceptional meteor showers will occur over the next 50 years, making it a valuable resource for both amateur and professional astronomers.

Astronomer PETER JENNISKENS completed his Ph.D. at Leiden University, the Netherlands, in 1992. He then worked as a National Research Council Associate at the Exobiology branch of the NASA Ames Research Center in Moffett Field, California, where he uncovered exotic properties of astrophysical ices, such as those in comets. Early in his studies, he became an amateur meteor astronomer with the Dutch Meteor Society. He has continued the study of meteor showers professionally at Ames and at the nearby SETI Institute, successfully predicting the α-Monocerotid meteor outburst in 1995. He went on to become the Principal Investigator of the NASA sponsored *Leonid Multi-Instrument Aircraft Campaign* that mobilized the scientific community to study 1998–2002 Leonid meteor storms. Amateurs continued to support his research. Dr Jenniskens is the chair of the Professional–Amateur Working Group of the IAU Commission 22 on meteoroids and interplanetary dust, and secretary of the IAU Commission 15 on the physical properties of minor bodies. In the course of writing this book, he identified the comet fragments remaining after the breakup that formed the meteoroid streams responsible for the Quadrantid and Phoenicid meteor showers, and in doing so he changed our ideas on how meteor showers predominantly originate.

METEOR SHOWERS AND THEIR PARENT COMETS

By Peter Jenniskens
The SETI Institute, California

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To my father,
Pierre Johan Jenniskens,

die altijd even bij me kwam staan
tijdens een waarneem aktie
totdat hij zelf ook een meteoor zag.

Contents

Tables

Preface

It was a warm summer evening in June in the light polluted Dutch city of Leiden in 1981 when I first sat down and gazed at the sky, waiting. A meteor appeared and I made a wish: "One more, please!" After 90 min, I had plotted four arrows on a chart of stars. That record still exists and has played a small role in the ongoing exploration of meteor showers. A very modest beginning to what has become a lifelong adventure.

In those days, we were resigned to the believe that our two most intense showers had no parent body, that meteor showers were as irregular as the weather (and more difficult to predict), that meteor storms came unannounced, and that this would always be so.

Today, we have reached an impressive milestone: about half of all large (>1 km sized) minor bodies approaching Earth's orbit have been discovered, two of which are the extinct comet nuclei that once produced the Geminid shower in December and the Quadrantid shower in January. The identification of the Quadrantid parent and several others were made in the course of writing this book.

Computers have revolutionized our insight into meteoroid stream dynamics. Meteor storm forecasting is now a reality. Over the years, amateur astronomers were witness to outbursts quite coincidentally. Now, storm chasing has become a popular pastime. In this book you will find much practical information about when to see meteor outbursts in the next 50 years and how they might manifest. We can look further into the future, but by 2050 the raw computing muscle of top-of-the-line computers is expected to have increased a million fold, at which time better predictions will surely be available than can be made now.

While writing this book, I found that many of our main meteor showers are the product of comet fragmentation. That new paradigm revives old ideas that had gone into submission after Fred Whipple proposed water vapor drag as the spring of meteoroid streams. If you are a professional astronomer, you will find in this book an overview of your work and that of colleagues who have helped illuminate the evolution of meteoroid streams, the physical properties of their parent bodies, their influx on Earth's atmosphere, their danger to satellites in orbit, and their role in the origin of life.

Acknowledgements

I have been fortunate to find a path in life that brings so much excitement from anticipation and surprise. While at NASA Ames and the SETI Institute, I have had the fortune of meeting many able researchers and program managers at NASA and the US Air Force, with open minds, who appreciate that meteors are a unique window on the universe around us and a door to both our past and our future.

Early on, *Hans Betlem* and *Rudolf Veltman* introduced me to the field. While observing, my father would stand by my side, and bear the cold just long enough to see at least one meteor. I found friends among members of the Dutch Meteor Society who were my teachers and guides, and who continued to support my work after I completed my studies at Leiden University and moved to NASA Ames Research Center and the SETI Institute. In the USA, I thank *Mike Koop* and members of the California Meteor Society for their unwavering support, and my partner in life *Charlie Hasselbach*, who smiled down on me and won my heart with meringue meteors of the sublime sort.

This book was written only because of the help of *Esko Lyytinen* and *Jérémie Vaubaillon*, who performed many numerical simulations. Others made contributions as well. *Bill Bottke* identified what might be extinct comet nuclei, *Peter Gural* calculated the visibility figures for future Moon impacts, *Giovanni Valsecchi* studied the link between 2003 EH$_1$ and comet C/1491 Y$_1$, *Emmanuel Jehin* observed 2003 EH$_1$, *Marco Fulle* studied the possibility of outbursts by ejection at aphelion, *Teemu Mäkinen* studied the water production rate of comet Tempel–Tuttle, and *Apostolos Cristou* calculated showers on other planets. *Brian Marsden* and *Daniel W. Green* of the Minor Planet Center provided comet light curve data and investigated several links between minor planets and meteoroid streams. *Joshua Kitchener* and copy editor *Louise Staples* assisted with the proof reading. Earlier versions of chapters were reviewed by *Sang-Hyeon Ahn*, *Josep Trigo*, *Iwan Williams*, and *Apostolos Cristou. Vladimir Porubčan*, head of the IAU Meteor Data Center, helped review the list of annual meteor showers.

For making other material available, I thank Shinsuke Abe, David Asher, Jack Baggaley, Hans Beltem, Nicholas Biver, Peter Brown, Donald Brownlee, Maurice Clark, Tony Cook, Gabriele Cremonese, Marco Fulle, Chet Gardner, Paul Gitto, Peter Gural, Bo Gustafson, Robert Haas, Cathy Hall, David Harvey, Jane Houston-Jones, David Hughes, Vincent Icke, Eric James, Jim Jones, Hideki Kondo, Mike Koop, Marco Langbroek, Steven Lee, Marc de Lignie, Steve Lowry, Esko Lyytinen, Paul D. Maley, Keith Mason, Neil McBride, Dick McCrosky, Bob McMillan, Karen Meech, Wil Milan, Koen Miskotte, Rick Morales, Kenton Parker, Vladimir Porubčan, Tim Puckett, Jim Richardson, Galina Ryabova, Mikiya Sato, George Rossano, Ed Schilling, Seth Shostak, Chikara Shimoda, Pavel Spurný, Walter Steiger, Hans Stenbeak-Nielsen, Casper ter Kuile, Josep Trigo-Rodriguez, Jérémie Vaubaillon, Jun-Ichi Watanabe, Hal Weaver, Paul Wiegert, Iwan Williams, Jeff Wood, *NASA*, *ESO*, the astronomical journals of *MNRAS*, *A&A*, and many others. Ilkka Yrjölä and other participants in Global-MS-Net provided the radio-MS observations that are presented here. I thank *Harm Habing* of Leiden University, *Werner Pfau* of Jena University, and *Didier Despois* of the University of Bordeaux for their support and hospitality, and for creating the conditions needed to write this book. Over the years, I received support in my studies from the NASA Planetary Astronomy and Planetary Atmospheres programs and the NASA Astrobiology program, with local help from *David F. Blake*, *Mark Fonda*, *Greg Schmidt*, *Paul Wercinski*, and *Dave Jordan* at the NASA Ames Research Center, and especially from *Frank Drake*, *Chris Chyba*, *Tom Pierson*, *Debbie Kolyer*, *Sue Lehr*, *Hal Roey*, and *Brenda Simmons* of the dedicated staff from the SETI Institute. Thank You.

Part I
Introduction

1

How meteor showers were linked to comets

When we wish upon a falling star, we appeal to an ancient belief that the stars represent our souls and a meteor is one falling into the hereafter.[1] In Teutonic mythology, for example, your star was tied to heaven by a thread, spun by the hands of an old woman from the day of your birth, and when it snapped, the star fell and your life had ended.[2]

The Greek philosophers were the first to speculate on the nature of things without regard to ancient myths. Especially the world views of *Aristotle of Stagira* (384–322 BC) in his 350 BC book *Meteorology*[3] were widely quoted for over two thousand years, embraced by Christian religion, and passionately defended until into the eighteenth century. The Greeks held that all matter in the Universe is made of the elements "earth," "water," "air," and "fire." Aristotle was of the opinion that *shooting stars*, because of their rapid motion, occurred relatively nearby in the realm of the element "fire" above the layer of "air" that is now called our atmosphere. He believed that shooting stars were not caused by the falling of stars, but were caused by thin streams of a warm and dry "windy exhalation" (a mixture of the elements fire and air) that had risen from dry land warmed by the Sun. Those exhalations would rise above the moist parts of the atmosphere containing clouds (mixtures of "air" and "water"), into the realm of "fire." The more and the faster a thing moves, the more it is heated by friction and the more apt it is to catch fire. Hence, when the motion of the heavenly bodies stir the "fire," the exhalations can burst into flame at the point where they are most flammable. Once ignited, the flame would run along the path of the vapor and thus create a "torch" – what we now call either a *fireball* or a *bolide* (βολιδεσ) meaning "thrown spear."

Aristotle's peers and predecessors used the Greek adjective μετεωρον in its plural form to refer to all "atmospheric phenomena or anything in the heavens." It is the substantive use of the Greek μετεωροσ which means "raised," "lofty," or in a more

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[1] E. Mozzani, *Le Livre des Superstitions – Mythes, Croyances et Légendes* (Paris: Bouquins, Robert Laffont, 1995), pp. 682–685.

[2] J. Grimm, *Deutsche Mythologie* (Berlin: Ferd. Duemmlers, 1876), p. 602.

[3] Aristotle (350 BC), *Meteorology*, book I, section 4, lines 32–34 (translation by E. W. Webster).

figurative sense, "sublime."[4] An eighteenth century meringue candy was called "meteors."

Meteor showers, Aristotle said, resulted from a very large exhalation that was scattered in small parts in many directions, when the hot "fire" element was squeezed from the cooling vapor like slippery fruit seeds pinched between one's fingers.

It is hard to picture Aristotle pinching his seeds and not knowing that meteor showers were radiating from a point in the sky (Fig. 1.1). But meteor showers were of no particular concern to Greek philosophers. Since Aristotle, meteor showers were considered part of our weather, a form of lightning. They were said to help sailors warn of upcoming storms.[5] For those less enlightened, meteor showers were either a good or a bad omen. The periodic meteor storm of April 3, 1095, for example, was mistaken by the Council at Clermont, France, *for a celestial monition that the Christians must precipitate themselves in like manner on the East*, when Pope Urban II called for the first crusades in November, 1095.[6]

The Leonid storm of 1833 changed all that and made meteor showers part of astronomy. It came at a time when *Isaac Newton*'s law of gravity had just been established. From that, it had been calculated how fast the Earth was moving around the Sun: with a speed of 30 kilometers per second (= km/s), or about 800 times the speed of a fast pitch in baseball. Even a small rock colliding with the Earth's atmosphere would find a violent end.

Meteor showers were now understood as being the result of *streams of meteoroids*, most no bigger than a grain of sand, approaching from one direction, before colliding with our atmosphere. Initially, this revelation created confidence that now all was understood, but predicting the return and activity of meteor showers proved to be as elusive as predicting the weather. In an age of rapidly expanding knowledge, many astronomers would start their career on a warm summer night during the Perseids, only soon to turn their attention to easier and more profitable problems such as Black Holes or the Age of the Universe.[7]

Only in the last ten years has the unyielding beast of a trillion particles finally been caged. We are not yet sure if all the bars will hold, but as in a zoo stocked for our pleasure, we now recognize a generous range of meteor shower manifestations, each providing clues about the minor planets at their source, which are nearly all comets.

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[4] J. A. Simpson and E. S. C. Weiner, *Oxford English Dictionary*, 2nd edn. 20 vols. (Oxford: Oxford University Press, 1989).

[5] L. A. Seneca (AD 62), *Naturales Quaestiones*, book I, sections 1.1–12, 14.1–15.6, book 2, sections 55.2–3. Translated by Thomas H. Corcoran (Cambridge, MA: Harvard University Press and London: Heinemann, 1971).

[6] J. W. Draper, *A History of the Intellectual Development of Europe* (New York: Harper Brothers, 1864); V. Clube and B. Napier, *The Cosmic Winter* (Oxford: Blackwell, 1990); A. McBeath, *WGN* **27** (1999), 318–326.

[7] M. Beech, Meteor astronomy: a mature science? *Earth, Moon Planets* **43** (1988), 187–194; D. Hoffleit, From early sadness to happy old age. *Comments Astrophys.* **18** (1996), 207–221.

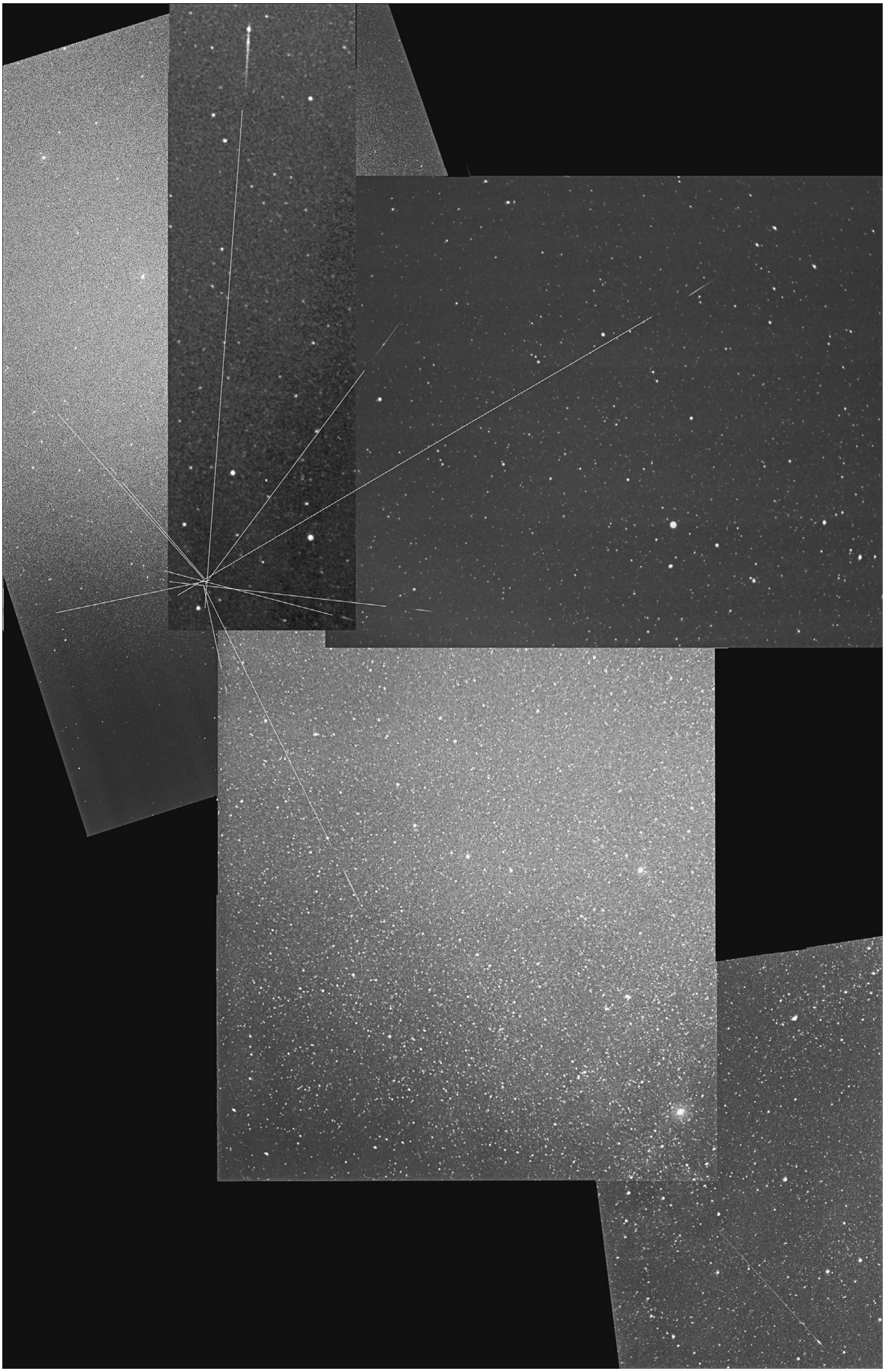

Fig. 1.1 The “radiant” of a meteor shower is the point in the sky from where the meteors appear to radiate, the head of Draco in this compilation of photographs of the 1985 Draconid outburst by members of the *Nippon Meteor Society*.

1.1 The quest to understand the nature of meteor showers

The first to keep careful records of meteor shower sightings were court-appointed astronomers in China, who were both time keepers and astrologers. Their motivation to do so was rooted in an eastern culture that considered its ruler "the emperor of all under heaven," the earthly counterpart of the heavenly god *Shang-ti*. The emperor maintained the harmony of Heaven and Earth by his actions in following the ritual and the prescripts of his forefathers precisely.[8] Any unrest in the sky was seen as a sign that something was amok with the emperor's rule. The astronomers at the royal court would gather such information from all over the empire. This included sightings of comets, fireballs, and meteor showers.

Meteor showers were known as periods of unusually high meteor rates. We now know that some repeat each year, called the *annual meteor showers*, and that there are also irregular showers called *meteor outbursts*. An example of meteor outbursts in recent years are those from the November Leonid showers. The rate in 1994, for example, was much higher than in 1995 ("Leo" in Fig. 1.2).

The oldest account linked to a modern shower is the exceptional *Lyrid* outburst of March 16, 687 BC (Julian calendar) during the Chou dynasty period, when it was written: "In the middle of the night, stars fell like rain." This account dates from more than two centuries before the philosopher *Confucius* (K'ung Fu-tze, 551–470 BC) and others like him transformed old ideas of knighthood into teachings of virtuous behavior as the basis of a good state.[9] We will explain later why this particular shower was seen so long ago.[10]

There are hundreds of such records in the Chinese, Japanese, and Korean literature. Table 1 gives a list of dated accounts prior to 1900, mostly compiled by Ishiro Hasegawa from Japan and Sang-Hyeon Ahn from Korea, building on work started in 1841 by *Edouard Biot*.[11] Table 1 also includes scattered references to clay tablets written in cuneiform script by the pre-Greek priest-astronomers of Mesopotamia from about 747 to 75 BC, who observed the Moon and planets for timekeeping and later also astrology, as well as references dating from the post-Greek Arabic Middle-East and from medieval Europe.

Most accounts are readily identified as the summer Perseids (Fig. 1.3), but many have no known present-day counterpart. Some are mere second-hand accounts of bright fireballs, or normal meteor activity seen in exceptionally clear nights (no Moon, no haze). The rest tell a story about meteor showers changing in time and place and about some very fortunate observers, now long forgotten.

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[8] A. Pannekoek, *A History of Astronomy* (London: Allen and Unwin, 1961, New York: Dover, 1989).

[9] *Ibid.*

[10] C. P. Olivier, *Meteors*. (Baltimore, MD: Williams & Wilkins, 1925), p. 6. Olivier believes this account could have been a meteorite fall, from the alternative translation "there fell a star in the form of rain."

[11] M. Éd. Biot, *Catalogue Général des Étoiles Filantes et des Autres Météores Observés en Chine pendent 24 Siècles* (Paris: Imprimerie Royale, 1841).

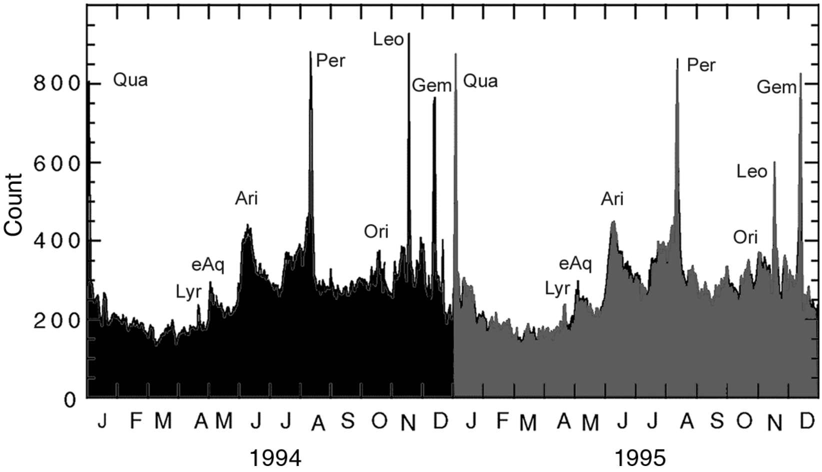

Fig. 1.2 Rate hikes in the daily count of meteors in the years 1994 and 1995, measured by Ilkka Yrjölä of Kuusankoski, Finland, by means of counting reflected radio signals from far away TV or radio stations. Note how the rates repeat year after year.[12]

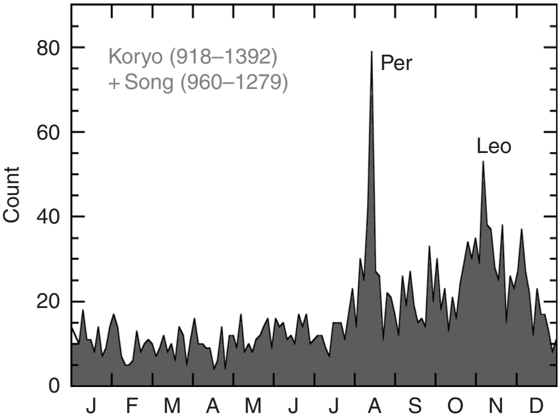

Fig. 1.3 Daily variations in meteor activity in the Middle Ages as reflected in the total daily number of shower reports from the Chinese Song and Korean Koryo dynasties, gathered by Sang-Hyeon Ahn.[13] Note the absence of the now prominent Quadrantid (Boo) and Geminid (Gem) showers.

Today, the most significant annual variations in meteor rates are due to the showers of *Quadrantids* (= Bootids) in early January, the *Lyrids* in April, the *η-Aquariids* in May (southern hemisphere), the *δ-Aquariids* in July, the *Perseids* in August, the *Orionids* in October, the *Taurids* and *Leonids* in November, and the *Geminids* in December. These

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[12] I. Yrjölä and P. Jenniskens, Meteor stream activity VI. A survey of annual meteor activity by means of forward meteor scattering. *Astron. Astrophys.* **330** (1998), 739–752.

[13] S.-H. Ahn, Meteoric activities during the 11th century. *Mon. Not. R. Astron. Soc.* **358** (2004), 1105–1115; S.-H. Ahn, Meteors and showers a millennium ago. *Mon. Not. R. Astron. Soc.* **343** (2003), 1095–1100; S.-H. Ahn, Catalog of meteor showers and storms in Korean history. *J. Astron. Space Sci.* **21** (2004), 39–72.

showers are named after the constellation from where their meteoroids appear to approach us: Bootes, Lyra, Aquarius, Perseus, Orion, Taurus, Leo, and Gemini.

The discovery of the *radiant*, more than the periodic increase of rates, defines what is a *meteor shower*. That discovery was made in 1833, after elevated Leonid rates were first seen in 1831 and then a storm of Leonids was noticed by city guards in Europe on the night of November 12, 1832.[14] When the phenomenon repeated the next year, Professor *Denison Olmsted* (1791–1859)[15] at Yale College, "through the kindness of a friend, was awaked in season to witness the spectacle in much of its grandeur," the results of which were swiftly published in the *New Haven Daily Herald*. There were widespread reports of a radiant placed close to the star γ Leonis, stationary during the night.

Olmsted recognized that the radiant phenomenon was caused by bodies moving on parallel tracks entering Earth's atmosphere from the general direction of γ Leonis. Olmsted reached this conclusion based on the 1794 thesis by *Ernst Florens Friedrich Chladni* (1756–1827),[16] who had argued how meteors had to be caused by solid *meteoroids* entering Earth's atmosphere at high speed. Chladni wanted observers to measure the height of the meteors in the atmosphere by triangulation from simultaneous observations at two separated observing sites. In 1798, *Johann Benzenberg* (1777–1846) and *Heinrich Wilhelm Brande*s (1777–1834), students at the University of Göttingen, were encouraged by their professor (who collaborated with Chladni) to follow up, and they proved that meteors were higher than other weather phenomena and indeed had to move at astronomical speeds.

It was then remembered that, 33 years earlier, the famous German scientist and traveler *Alexander von Humboldt* on an expedition to south and middle America had seen, and described, a similar meteor storm in the early morning of November 12, 1799, while in Cumaná, Venezuela. We now know that the meteors peaked that year around 06:15 UT in a massive pile up of dust trails. Von Humboldt wrote that people old enough to remember recalled that the same phenomenon was seen about 30 years before. A pattern was recognized. During the research for this book, Jérémie Vaubaillon and the author set out to investigate this anecdote and we discovered that there was only one storm that season, and that storm happened to be visible from South America at 06:18 UT on November 9, 1771 under similar circumstances albeit not as intense as the later storm (Chapter 15).

The discovery of periodic Leonids and the phenomenon of the radiant quickly led to the discovery of other meteor showers. The January *Quadrantids* (1835) and the

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[14] W. Olbers, Die Sternschnuppen. In *Jahrbuch für 1837*, ed. H. C. Schumacher. (Stuttgart: Cotta'schen Buchhandlung, 1837), pp. 36–64.

[15] D. Olmsted, Observations on the meteors of November 13th 1833. *Am. J. Sci. Arts* **25** (1834), 363–411; **26**, 132–174; A. C. Twining, *Am. J. Sci. Arts* **25** (1834), 320.

[16] E. F. F. Chladni, *Ueber Den Ursprung Der Von Pallas Gefundenen Und Anderen Aehnlichen Eisenmassen* (Riga: Hartknoch, 1794), 63 pp; E. F. F. Chladni, *Ueber Feuer Meteore Und Uber Die Mit Denselben Herabgefallenen Massen* (Wein: Heubner 1819), 424 pp.; M. Beech, The makings of meteor astronomy: part X. *WGN* **23** (1995), 135–140.

August *Perseids* (1835) were first made widely known by *Adolphe Quételet* in Brussels, founder of the Observatoire Royal de Bruxelles.[17] Quételet not only observed the Perseids, but found many earlier records, the oldest by the Dutch inventor of capacitance (the Leyden jar), the physicist Pieter (Petrus) van Musschenbroek (1692–1761),[18] who wrote in a publication that was printed in 1762: *Stellae (cadentae) potissimum mense Augusto post praegressum aestum trajici observantur, saltem ita in Belgio, Leydae et Ultrajecti.*[19]

In addition, a well-observed 1803 Lyrid outburst in the eastern United States led to the discovery of the weak annual April *Lyrid shower* in 1838 by *Edward Claudius Herrick* at Yale College,[20] to which, in October 1839, he added the discovery of the annual *Orionids*[21] (independently discovered also by Quételet[22] and Benzenberg). Johann Benzenberg[23] and *Eduard Heis* observed the Andromedids in 1838, following a 1798 sighting of an outburst by their colleague Brandes. Other major showers were not discovered until just after the next Leonid storm in 1866, which again raised interest in the topic of meteor showers.

For the next 150 years, visual meteor observations mostly concentrated on plotting meteors in search of new annual shower radiants. Best for that are *gnomonic* star *charts*, on which meteors move as straight lines and it is easily checked whether they radiate from a common circular area. British amateur astronomer *William Frederick Denning* of Bristol, witness of the 1866 Leonid storm at age 17, published thousands of such radiants at the turn of the century,[24] and several updates after that. He was so much respected as a meteor observer that the novelist H. G. Wells featured Denning as the "meteorite expert" (*sic*) in his 1898 *The War of the Worlds*. In 1935, the list was complimented with southern showers when New Zealander *Ronald Alexander McIntosh* published his *An Index to Southern Meteor Showers*.[25] Unfortunately, poorly drawn star charts and a common habit of accepting big circles for radiant association made many of these "showers" unreliable.

Better criteria were needed to recognize streams. This became possible in the mid-twentieth century when photographic and radar techniques first measured the atmospheric trajectory and speed of meteors and, from that, the orbit of the meteoroids in

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[17] A. Quételet, *Correspond. Math. Phys. IX*, **184** (1837), 432–441; J. Sauval, Quételet and the discovery of the first meteor showers. *WGN* **25** (1997), 21–33.

[18] P. Van Musschenbroek, *Introductio ad Philosophiam Naturalem* (Lugdani Batavorum: Luchtman, 1762).

[19] Loosely translated: "Falling stars are observed in the middle of August more than at other times in the year given the rate of observed trails seen at least in such places as Belgium, Leyden, and Utrecht."

[20] E. Herrick, *Am. J. Sci. Arts* **34** (1838), 398; **35** (1839), 366; **36** (1840), 358.

[21] E. Herrick, *Am. J. Sci. Arts* **35** (1839), 366.

[22] A. Quételet, Catalogue des principales apparitions d'etoiles filantes. *Mém. l'Acad. Roy. Sci. Belles-Lett. Bruxelles* **12** (1839), 1–56.

[23] J. F. Benzenberg, *Die Sternschnuppen* (Hamburg: Perthes, 1839), 339 pp, p. 244 (Orionids), p. 331 (Andromedids).

[24] W. F. Denning, General catalogue of radiant points of showers and fireballs observed at more than one station. *Mem. R. Astron. Soc.* **53** (1899), 202–292; see also M. Beech, W. F. Denning – the doyen of amateur astronomers. *WGN* **26** (1998), 19–34.

[25] R. A. McIntosh, An index to southern meteor showers. *Mon. Not. R. Astron. Soc.* **95** (1935), 709–718; G. W. Wolf, Ronald Alexander McIntosh – not just a southern meteor pioneer. In *Proceedings IMC Belogradchik 1994* (Potsdam: International Meteor Organization, 1994), pp. 78–85.

space. New meteoroid streams were discovered now from their similar orbits. In one study, as much as 65% of all bright meteors were assigned to (mostly minor) meteor showers.[26]

Even with these tools, it continued to be a problem to recognize diffuse streams among the sporadics. This is especially the case for the imprecise orbits measured by radar in the past. Because different sets of sporadic meteoroid orbits were mixed in, and because showers were observed only intermittently, the same stream is often reported under a different name, creating much confusion about its identity. Many of the reported "streams" are groupings of meteoroids that do not originate from the same parent body.

1.2 Meteoroid streams as debris from comets

The association of meteor showers with comets was made only when it became clear how comets and meteoroids orbit the Sun. The first step was taken when observers of the 1833 Leonid storm, such as Olmsted, wanted to share their experiences and set out to predict the next Leonid storm. Olmsted recognized their periodic nature and suggested that clouds of meteoroids were moving in orbits around the Sun every six months, mistakenly attributing the 1803 *April Lyrid* outburst to the same repeating phenomenon responsible for the two spectacular Leonid storms of 1832 and 1833![27]

These ultra-short orbital periods tended to be believed, misled too by the discovery that some showers returned annually. From the now translated Chinese accounts, Herrick showed in 1837–38 that meteor showers were periodic on a sidereal rather than a tropical year.[28] When Quetelet raised once again the possibility of a link with the weather, mathematician *Hubert Anson Newton* of New Haven (in 1863) pointed out that the meteor showers did not come at the same time in the season. Unlike the weather, the Julian date of past Leonid storms had progressed by a month from October 13 in AD 902 to November 13 in 1833. During that time, the Earth's spin axis had gradually changed position. It completes a full circle every 25 792 years, a phenomenon called *precession*. As a result, the seasons fall progressively at a different position in Earth's orbit (the duration of a siderial and a tropical year differ by 1 day in 70.613 34 years). After taking this into account, Newton found that those Leonid storm dates nearly corresponded to the same position of Earth in its orbit.[29]

Not exactly to the same position, however. There was a remaining shift in the time of the peak, amounting to +29 min per orbit of 33.25 yr, which had to be on account of

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[26] L. G. Jacchia and F. L. Whipple, Precise orbits of 413 photographic meteors. *Smithsonian Contrib. Astrophys.* **4** (1961), 97–129.

[27] D. Olmsted, Observations on the meteors of November 13th, 1833. *Am. J. Sci. Arts* **25** (1834), 363–411; **26**, 132–174; D. Olmsted, *Letters of Astronomy Addressed to a Lady* (New York: Harper & brothers, 1849), pp. 359–364.

[28] E. C. Herrick, *Am. J. Sci. Arts* **33** (1837), 176; **33** (1838), 354.

[29] H. A. Newton, Evidence of the cosmical origin of shooting stars derived from the dates of early star showers. *Am. J. Sci.* **36** (1863), 145–147; H. A. Newton, The original accounts of the displays in former times of the November Star-Shower. *Am. J. Sci.* **37** (1864), 377–389; **38**, 53–61; D. W. Hughes, The history of meteors and meteor showers. *Vistas Astron.* **26** (1982), 325–345.

other influences. Newton was also struggling with the periodicity of the returns. He favored periods of 354 d (1 − 1/33.25 yr); another suggestion was 375 d (1 + 1/33.25 yr), and another 33.25 yr. He predicted a return of the storms in 1866.

Astronomer John Couch Adams, better known for his role in the discovery of Neptune, later proved that only the last solution could be true. In April, 1867 Adams figured that the meteoroid orbits were also precessing and calculated that this +29 min/orbit was well matched by the expected combined effect in rotating the orbit from the gravitational pull by Jupiter (+20 min), Saturn (+7 min) and Uranus (+1 min), but only if the orbital period was the longer 33.25 yr. The proposed shorter orbits by Olmsted and Newton would not do.[30]

Before Adams made his arguments about the long orbital period of the Leonid shower, *Giovanni Virgínio Schiaparelli* (1835–1910) at Milan, of Mars *canali* fame, had found that most meteoroid orbits had to be very elongated. Mainly, because meteors were seen in the evening as well as morning hours in a numbers ratio of 1.4 ($=\sqrt{2}$), the ratio of speeds for meteoroids in circular and parabolic orbits. Shiaparelli concluded that meteoroids in general were moving on near-parabolic orbits. In a series of Italian papers that formed the basis of his 1866 book: *Note e riflessioni intorno alla teoria astronomica della stelle cadenti*,[31] he showed that the orbit of the Perseids, if nearly parabolic in shape, was very similar to *Theodor Ritter von Oppolzer*'s orbit for comet 1862 III (Swift–Tuttle).[32] Schiaparelli had discovered the source of the meteoroids.

Schiaparelli failed to find a comet for his Leonid orbit, because he used γ Leonis as the approximate position of the radiant, which was several degrees off. The first comet of 1866 (55P/Tempel–Tuttle) was recognized as the parent of the Leonid storms[33] shortly after *Urbain Jean Joseph Le Verrier* in France derived an orbit from a better radiant position in 1867.[34]

A third shower parent was identified in the metropolis of Vienna in 1867, when *Edmond Weiss*, looking for comets passing near Earth's orbit, found that the 1861 comet C/1861 G_1 (Thatcher) passed within 0.002 AU on April 20 and found evidence of an April Lyrid shower in the literature.[35] Later that year, *Johann Gottfried Galle* calculated the Lyrid orbit, assuming it was a parabola, and confirmed the association. He also first pointed to the Chinese account from 687 BC as a possible early Lyrid shower sighting.

It was now understood, given that a cloud of meteoroids from a distance would look like a comet, that comets and meteoroid streams, properly speaking, were identical.

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[30] J. C. Adams, On the orbit of November meteors. *Mon. Not. R. Astron. Soc.* **27** (1867), 247–252.

[31] G. V. Schiaparelli, *Note e Riflessioni intorno Alla Teoria Astronomica delle Stelle Cadenti* (Firenze: Stamperia Reale, 1867), 132 pp. (Translated into German in 1871. *Entwurf einer astronomischen Theorie der Sternschnuppen*. Stettin: Th. V. d. Nahmer VIII, 268 pp, long the standard book on meteor astronomy.)

[32] M. J. V. Schiaparelli, Sur la relation qui existe entre les comètes et les étoiles filantes. *Astron. Nachr.* **68** (1967), 331.

[33] J. C. Adams, On the orbit of November meteors. *Mon. Not. R. Astron. Soc.* **27** (1867), 247–252.

[34] U. J. LeVerrier, *Comptes Rendus* **64** (1867), 94.

[35] E. Weiss, Bemerkungen über den Zusammenhang zwischen Cometen und Sternschnuppen. *Astron. Nachr.* **68** (1867), 381.

2

What is at the core of comets?

The most spectacular result of recent space missions to comets has been to show the spring of meteoroid streams, first when Giotto visited Halley in 1986. The return of comet Halley was highly anticipated. I was an undergraduate student of astronomy at *Leiden University* in the Netherlands and was invited to be a tour guide on a chartered DC-9 airplane to watch the comet above the usual deck of clouds. Two hundred people eager to see the scourge of legend sparkle in the sky paid $50 and were given six ten-minute laps over the North Sea, each time providing a new group a seat at the windows. I recall spending some extra time with an eyewitness of comet Halley's previous return in 1910. She had the gray hair and worn face of one outlasting Halley's 76 yr orbit. Sadly, her eyesight had suffered over the years and she never found the faint $+4^{m}$ fuzz of light in the constellation of Capricorn. She was thrilled nonetheless. This was her first time in a plane, and my first astronomical expedition.

The word *comet* comes from the Greek κομετεσ = "the hairy one." The Chinese astronomers called these objects *hui* or "broomstars" and tracked their position in the constellations, moving from one group of stars to the next over days or sometimes many weeks on account of their great distances. From a distance, these inferior planets of our solar system are fuzzy blobs, sometimes with a diffuse tail pointing away from the Sun. Prior to AD 1577, comets and shooting stars were all considered meteors (Fig. 2.1).[1] Even today, popular culture does not always make the correct distinction between comets, the minor planets in space, and the meteors caused by their debris impacting on Earth's atmosphere.

Danish astronomer *Tycho Brahe* (1546–1601) first proved that comets belong in the realm of astronomy by demonstrating from the lack of parallax between viewing the comet in the evening and the morning that the bright comet of 1577 was at least four times farther from Earth than the Moon. In 1610, amateur Sir William Lower proposed correctly that comets move in elongated ellipses, while Robert Hooke and Giovanni Borelli thought cometary orbits might be so elongated as to be barely open

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[1] Illustration of Fig. 2.1 is from: A. M. Mallets, *Beschreibuing des ganzen Welt Kreisses* (Frankfurt am Main: Johann Adam Jung Verlag, 1719) (republished from: *Description de l'Universe* (Paris, 1684)). It illustrates the comment that comets, according to Apollonius, were considered part of the "wandering stars" by the Chaldeans (612–539 BC), who were the "New Babylonians" following the fall of the Assyrian empire.

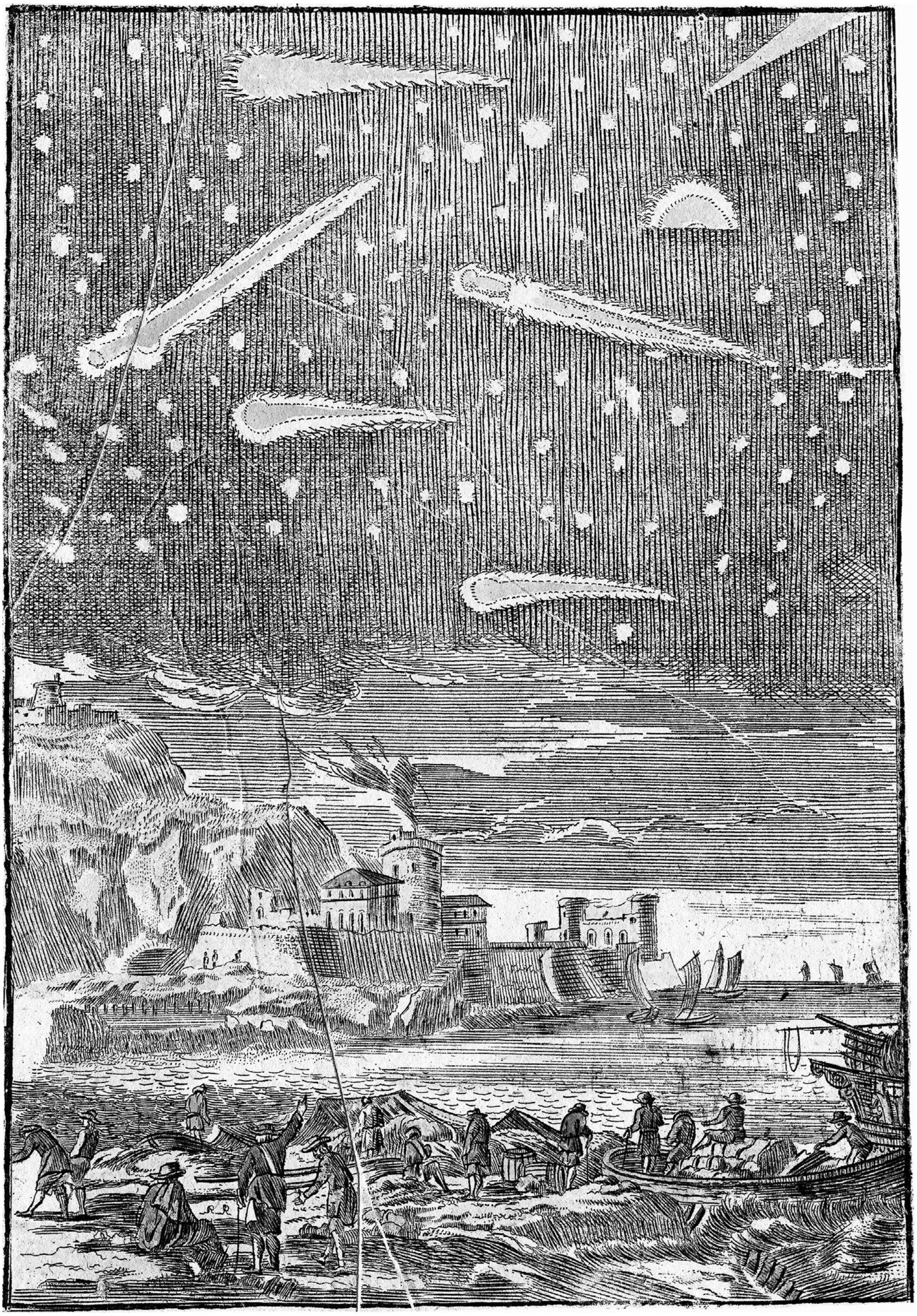

Fig. 2.1 Comet types. A seventeenth century engraving by Mallets, depicting comets as if a shower of meteors.[2]

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[2] *Ibid.*

ended, so-called *parabolic orbits*. *Isaac Newton* (1643–1727) in his 1687 book *Principia Mathematica* applied his new theory of gravitation, the core of which was that everything attracted everything else, to show that the comet of 1680 moved in an elliptical orbit, albeit nearly parabolic.

In the year 1705, British astronomer *Edmond Halley* (1656–1742) investigated the orbits of 24 comets and found that those of 1531, 1607, and 1682 were similar.[3] In light of Newton's new theory of gravity, Halley recognized that the slightly different episodes between returns came about on account of the gravitational attraction of the planets, called *planetary perturbations* of the orbit, and predicted the return of the comet in December of 1758. Halley died before the comet was seen again on Christmas day that year. This is now the first numbered and officially named comet, *1P/Halley*.

1P/Halley has been seen on each return since the earliest recorded sighting from China in 239 BC. Famous returns include that of AD 1066, the year which began the Norman conquest of England following the battle of Hastings, after which comet Halley was immortalized in fine needle work on the *Bayeux Tapestry*. The recovery in 1758 proved conclusively that Newton's law of gravity was valid as far out as comet Halley traveled from the Sun: a distance three times that of Saturn, the outermost planet known at the time.

The first scientific study of comets came with the next return of 1P/Halley in 1835, when more sophisticated instruments were available. Jets were observed for the first time in comet images, which led the German astronomer *Friedrich Wilhelm Bessel* (1784–1846) in 1836 to postulate, much ahead of his time, that dust particles were ejected in the direction of the Sun, which were then pushed back away from the Sun by an unknown repulsive force[4], now know to be radiation pressure from sunlight.[5]

2.1 The comet nucleus

The big riddle has always been what force could drive the ejection of meteoroids. Until into the twentieth century, many thought that comets were a *flying sand bank*,[6] a cloud of dust and pebbles, held together by their own mutual gravitational attraction. It was assumed that the Sun's tidal force (the difference in gravitational attraction between one side of the comet and the other) was enough to bring the meteoroids from moving around each other to moving in independent orbits. Indeed, seen from a great distance, meteoroid streams were expected to look like comets.

This impression was enforced when comet 3D/Biela broke apart in 1843 and was last seen one orbit later in 1852, and shortly thereafter spectacular storms of Andromedids were seen in 1872 and 1885. At the time, this took away much of the

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[3] E. Halley (1705) *Astronomiae Cometicae Synopsis*. Philosophical Transactions.

[4] F. W. Bessel Beobachtungen ueber die physische Beschaffenheit des Halley'schn Kometen und dadurch veranlasste Bemerkungen. *Astron. Nachr.* **13** (1836), 185–232.

[5] S. A. Arrhenius, On the physical nature of the solar corona. *ApJ*. **20** (1904), 224–231.

[6] H. Schellen *Die Spektralanalyse*. (Brauschweig: Westermann, 1870), 452 pp; R. A. Lyttleton, On the origin of comets. *Mon. Not. R. Astron. Soc.* **108** (1948), 465–475.

early nineteenth century fears that comets might cause devastation when hitting Earth. Instead, comets were now expected to merely cause a brilliant meteor storm. In 1948, the British astronomer *Raymond A. Lyttleton* developed this idea into a comprehensive scenario where comets were formed as a loose swarm of ice and dust at the birth of the solar system directly from the condensation of a stream of interstellar dust and gas particles.

In reaction to that, meteor astronomer *Fred Lawrence Whipple* argued in 1950 that there had to be a solid core with his *icy conglomerate model* of a comet nucleus, nicknamed the *dirty snowball model*.[7] Astronomers talk of "models" when they discuss a simplified picture of something otherwise too complex to grasp. Many comets kept arriving back in the Earth's neighborhood a few days earlier or later than expected from Newton's laws of gravity alone. A force other than gravitation (a so-called *nongravitational force*) was needed to explain why. Whipple pictured a solid object at the center of the comet, the *comet nucleus*, consisting of a conglomeration of water ice with dust grains imbedded. He figured that the evaporation of the ice would cause a reaction force, a rocket effect. In a second paper,[8] Whipple calculated how the flowing water vapor would drag solid meteoroids into the vacuum of space against the gravitational field of the remaining mass, for the first time illuminating the birth of a meteoroid stream.

The ejection of matter will push the comet gradually into a different orbit, but only if the push is different before and after passing the Sun. The light curve of the comet will tend to be asymmetric.[9] This is possible when the comet spin axis (constant with respect to the stars) is tilted, in such a way that the comet presents a different side to the Sun. The change of the orbit is often expressed in terms of units "A_1," the radial *nongravitational acceleration* of the comet (radial as in acting along the line Sun–comet), and "A_2," the transverse nongravitational acceleration perpendicular to A_1 in the orbital plane. There is also a third term "A_3," the transverse nongravitational acceleration normal to the orbital plane responsible for changes of the orientation of the orbit.[10]

Always shrouded in a mist of dust particles, this "nucleus" was one of the solar system's best kept secrets. At the time, Whipple's postulation of a solid center was only that. That veil was lifted only by the spectacular images from the European *Giotto* spacecraft in 1986. Giotto traveled in the essential company of two Russian "VeGa" spacecraft (for Venus Galley – signifying an extended mission to 1P/Halley after a

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[7] F. L. Whipple, A comet model. I. The acceleration of comet Encke. *Astrophys. J.* **111** (1950), 375–394.

[8] F. L. Whipple, A comet model. II. Physical relations for comets and meteors. *Astrophys. J.* **113** (1951), 464–474.

[9] M. Festou, H. Rickman and L. Kamél, The origin of nongravitational forces in comets. In *Asteroids, Comets, Meteors III. Proc. Meeting, Uppsala, Sweden, 12–16 June 1989*, ed. C.-I. Lagerkvist, H. Rickman, B. A. Lindblad, M. Lindgren, *Astron. Obs.* (1989), pp. 313–316.

[10] A_i is defined as $A_i = a_i/g(r)$, where the empirical function $g(r)$ is the ice sublimation rate, which changes with the heliocentric distance, and a_i is the orbital acceleration vector induced by the evaporation. Both are usually expressed in units of 10^{-8} AU/d^2. B. G. Marsden, Comets and nongravitational forces II. *Astron. J.* **74** (1969), 720–734.

flyby of Venus).[11] That year, I was glued to the television in anticipation. These remote travelers were penetrating the dense haze of the comet, their TV cameras ready, and just as in a dense fog we were expecting to see the actual nucleus emerge in crisp detail upon arrival. When the first pictures were finally broadcast, they were presented as contour images in false colors of pink, green, and yellow, leaving even the brightest commentators biting the dust. Nobody could tell what we were looking at, except that there was something bright in the center of the pictures at which the cameras were automatically pointing. I did not know it at the time, but that bright blob was the birth of a meteoroid stream!

Broadcasters were still clueless, talking about the 8 min it would take for radio signals to arrive on Earth and how wonderfully the mission was unfolding, when in the background mission control in Garching was clearly in disarray. Contact had been lost with the Giotto spacecraft just after the moment of closest approach. Later it was found that the spacecraft was knocked into a wobble by a collision with a large meteoroid and the transmission was interrupted. Responsible for that near knockout was the sort of meteoroid that could have made a really nice Orionid or η-Aquariid meteor for some star gazer in the far future. Sadly enough, this particle did not survive the encounter.

The next day's six o'clock news finally showed the now familiar grayscale image of Halley's nucleus (Fig. 2.2). Whipple's solid core was a pitch-black rock covered with mountains and valleys, later measured at 15.3 by 7.2 by 7.2 km. Compare that to Mount Everest, which stands tall at only 8.85 km. This comet was shaped like a potato, covered by circular depressions that, in hindsight, were probably impact craters.[12] Only 4% of sunlight was reflected from the surface, a fraction called the *albedo*. That meant that the comet surface was as dark as charcoal and freshly paved asphalt road surfaces.

Since that time three other comets have been visited by NASA probes: 19P/Borrelly by Deep Space One, comet 81P/Wild 2 by Stardust, and comet 9P/Tempel 1 by Deep Impact. Comet 19P/Borrelly measured 8.8 by 3.6 by 0.8 km. Borrelly was even darker than Halley: only 2.9% of light on average reflected from the surface.[13] Looking at the image of comet Borrelly in Fig. 2.2, it is not hard to understand that after having lost kilometers of overlaying material this nucleus is only a small remaining core of what used to be a much larger comet. The result is a fairly smooth surface. In contrast, comet 81P/Wild 2 (pronounced "Vilt 2") may still have the impact craters from its formation time: a much more irregular surface with deep flat-bottomed pits. Its shape was almost spherical and the nucleus measured about

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[11] The French space agency CNES cooperated in the VeGa program, which made it possible to deploy a copy of the German Giotto dust composition experiment (PIA) onboard the VeGa 1 (PUMA-1) and VeGa 2 (PUMA-2) spacecraft despite Cold War restrictions at the time.

[12] P. J. Stooke, A. Abergel, Morphology of the nucleus of comet P/Halley. *Astron. Astrophys.* **248** (1991), 656–668.

[13] D. T. Britt, D. C. Boice, B. J. Buratti *et al.*, The morphology and surface processes of comet 19P/Borrelly. *Icarus* **167** (2004), 45–53; B. Buratti, M. D. Hicks, L. A. Soderblom *et al.*, Deep Space 1 photometry of the nucleus of comet 19P/Borrelly. *Icarus* **167** (2004), 16–19.

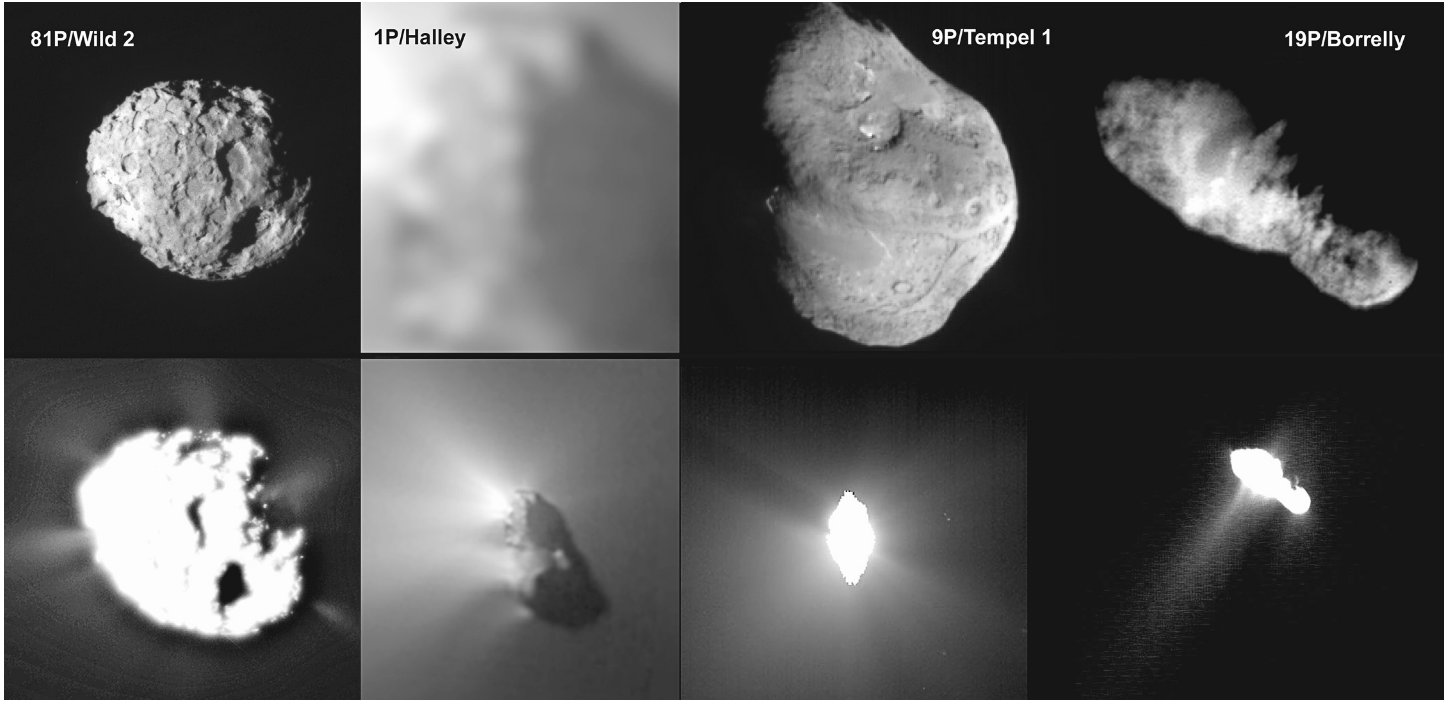

Fig. 2.2 Young, older, old: the nucleus of comets 81P/Wild 2, 1P/Halley, **9P/Tempel 1, and 19P/Borrelly**. Stardust was about 500 km (311 miles) from the nucleus of 81P/Wild 2 when it took the picture on the left, showing flat bottomed craters and a dozen faint jets. Photo: NASA/JPL. Comet 1P/Halley, parent of the Orionid and η-Aquariid showers, was imaged by the Giotto spacecraft prior to its closest approach, which occurred on March 14, 1986 at 00:03:02 UT at a distance of 596 km. Photo: MPI für Aeronomie, Katlenburg-Lindau, ESA. Comet 9P/Tempel 1 approximately 5 min before Deep Impact's probe smashed into its surface on July 04, 2005, at 05:45 UT. This image was taken by the impacting targeting sensor on the probe. Photo: NASA/JPL-Caltech/UMD. 19P/Borrelly was observed by the Deep Space One probe on September 22, 2001. Photo: NASA/JPL.

5.5 by 4.0 by 3.0 km.[14] The 8 by 5 by 5 km sized comet 9P/Tempel 1 had terrain common to both comets, except for having rigid craters on the older terrain and for having a more facetted young terrain.

Indeed, most known comets have sizes of the order of 1–10 km. Very few comets are known to be smaller than 1 km across. Among the biggest comets, and the most spectacular in recent years, was comet *C/1995 O_1* (*Hale–Bopp*), which was brighter than the star Vega for 7 weeks in the spring of 1997. The nucleus of this comet has been estimated at 60 ± 20 km diameter.[15] And there are much larger comets out there!

2.2 The birth of a meteoroid stream

As the smoke of a big fire, the jets of comet 1P/Halley scattered the bright sunlight and put the dark nucleus in a glowing frame (Fig. 2.2). The jets of dust and molecules also made the Giotto pictures a poignant reminder that comets in the inner solar system are in the process of dying. Gradually losing material in fountains of meteoroids until, at last, the comet falls to dust. Multiple jets on Halley originated from two regions on the nucleus. Including seeps over the remainder, only 10–15% of the surface was active. On Borrelly, one strong jet and two fainter jets were observed near the northern pole of the spinning nucleus, while about 10% of the day-side surface was actively emitting water vapor. In contract, the fresher looking 81P/Wild 2 had a dozen jets (Fig. 2.1).

We do not know how the landscape will look on a human scale, except that it will be as dark as coal with a hazy sky overhead (Fig. 2.3). At the time of writing, we are still years away from landing on the surface of a comet for the first time. The satellite Rosetta has been launched to do so.

The surface of the nucleus is expected to be covered in a thick layer of meteoroids that have fallen back in the gravity field of the comet. Deep Impact showed that layer to be very fluffy and porous, with a bulk porosity of $>60\%$ and a bulk tensile strength of ~ 100 Pa. The crust acts as insulation against the heat of the Sun, protecting the ice below.

Jets might arise from landslides on steep slopes that expose the fresh ice underneath. NASA's Cassini mission observed such slides from the subsidence of the steep crater walls on the Saturn moon Phoebe (Fig. 2.4). The moon is pocketed with impact craters. Interestingly, bright spots were also observed on comet 82P/Wild 2 by Stardust (Fig. 2.4) and on comet Tempel 1 by Deep Impact, where the spots are only tens of meters in size and are not always found on steep slopes.

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[14] Z. Sekanina, D. E. Brownlee, T. E. Economou, A. J. Tuzzolino and S. F. Green, Modeling the nucleus and jets of comet 81P/Wild 2 based on the stardust encounter data. *Science* **304** (2004), 1769–1774; A. J. Tuzzolino, T. E. Economou, B. C. Clark, P. Tsou, D. E. Brownlee, S. F. Green, J. A. M. McDonnell, N. McBride and M. T. S. H. Colwell, Dust measurements in the coma of comet 81P/Wild 2 by the dust flux monitor instrument. *Science* **304** (2004), 1776–1780; S. F. Green, J. A. M. McDonnell, N. McBride, M. T. S. H. Colwell, A. J. Tuzzolino, T. E. Economou, P. Tsou, B. C. Clark and D. E. Brownlee, The dust mass distribution of comet 81P/Wild 2. *J. Geophys. Res.* **109** (2004), E12S04.

[15] Y. R. Fernández, The nucleus of comet Hale–Bopp (C/1995 O1): size and activity. *Earth, Moon, Planets* **89** (2002), 3–25.

Fig. 2.3 Comet nucleus surface (author's artist impression, drawn prior to the 81P/Wild 2 encounter).

Several other scenarios have been proposed to explain the jets. Some suspect that the jets escape from narrow openings in the roof of still hidden subterranean caverns, in which case the bright spots could be areas of condensation of vapor around the cold vent. In such caves, water vapor pressure can build up, ejecting gas and dust at higher speeds. This would help to explain the very narrow width of the jets, only $\sim 5^\circ$, but leaves unanswered how the heat of sunlight can penetrate deep down into the caves.

Others suspect that the jets emanate from flat-bottomed sinkholes,[16] created when the roof of a subterranean cave collapsed. Vapor flowing from the walls will

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[16] H. U. Keller, J. Knollenberg and W. J. Markiewicz, Collimation of cometary dust jets and filaments. *Planet. Space Sci.* **42** (1994), 367–382.

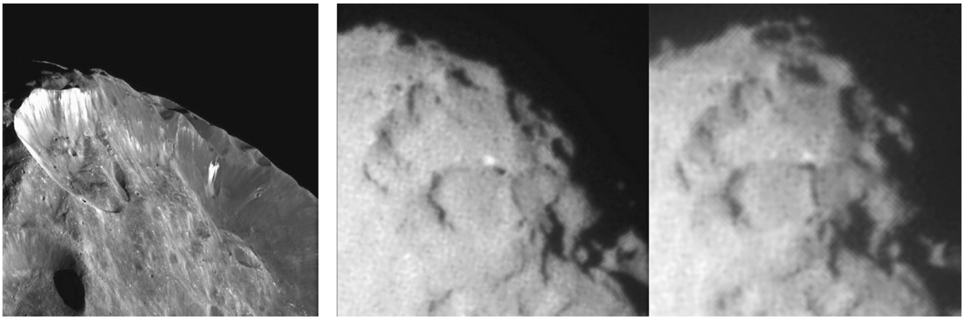

Fig. 2.4 Left: Saturn's moon Phoebe as seen by the Cassini–Huygens mission. The crater on the left is about 45 km (28 miles) in diameter. Photo: NASA/JPL. **Right: Stereo image of the 81P/Wild 2 surface**, showing a bright spot, flat-bottomed impact craters, and upturned ridges. Photo: NASA/JPL – Stardust.

concentrate in a narrow beam in the middle of the pit, creating a dust spike and a jet cone.[17] Comet 82P/Wild 2 had such flat-bottomed holes. However, these are now understood to be relatively old craters resulting from impacts in cohesive porous material.[18] If so, it remains a puzzle why some small fragments of the old surface still stand as tall and steep pinnacles.

One of the great discoveries of satellite missions is that caves and crevasses can also come from the internal structure of the comet. It turns out that the comets encountered so far have a low *bulk density*. When the volume of the nucleus can be measured from TV images, then the density equals the mass per volume. The mass of a comet nucleus is measured from the magnitude of the rocket effect on the orbit as envisioned by Whipple.

When something has a density of less than 1.04 g/cm^3, it will float in liquid water at room temperature. With solid rock at 3.5 g/cm^3 and ice at 0.96 g/cm^3, a comet nucleus was expected to measure somewhere in between. Instead, the density of comet 1P/Halley is only 0.55 ± 0.25 g/cm^3 and comet Borrelly has a density of 0.24 ± 0.06 g/cm^3. Less than pinewood at 0.8 g/cm^3. Halley's *Orionid shower* meteoroids have a similar density of 0.23 g/cm^3, or larger if fragmentation is considered,[19] but that is after the meteoroid has lost all ice and only a loose assembly of minerals and organic matter remains. Hence, some of the low density of comets has to be on account of the bulk morphology.

Internal caves and crevasses can result from a loose packing of km-sized cometesimals into a *rubble pile* (Fig. 2.5).[20] *Cometesimals* are the smaller units that once came together under mutual gravity to form a comet. In my opinion, this leads to a natural

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[17] T. I. Gombosi, A heuristic model of the comet Halley dust size distribution. *ESA SP* **250** (1986), 167–171.

[18] D. E. Brownlee, F. Horz, R. L. Newburn *et al.*, Surface of young Jupiter Family Comet 81P/Wild 2: view from the Stardust spacecraft. *Science* **304** (2004), 1764–1769.

[19] F. Verniani, Meteor masses and luminosity. *Smithsonian Contrib. Astrophys.* **10** (1967), 181–195.

[20] P. R. Weissman, Are cometary nuclei primordial rubble piles? *Nature* **320** (1986), 242–244.

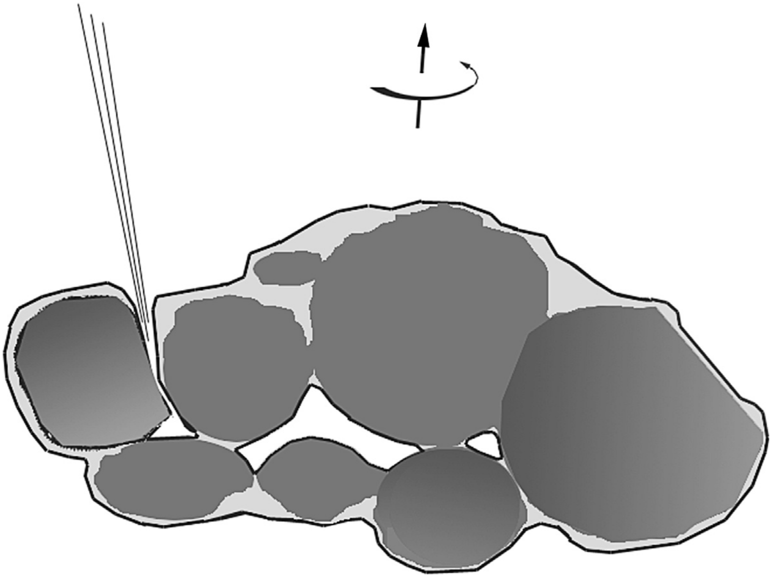

Fig. 2.5 Rubble pile nucleus with jet from crevasse between cometesimals, opened up by centrifugal forces.

formation mechanism for jets: outgassing will spin-up the nucleus leading to centrifugal forces on the cometesimals. These can open up deep crevasses between the cometesimals, resulting in jets being directed towards one of either of the spinning poles of the comet nucleus (Fig. 2.5).

Finally, dust grains can be dragged into space by escaping from millions of pores in the crust of the comet. It has even been suggested that such *seeps* can cause jets as a result of the larger scale topography of the comet.[21] Laboratory experiments show that even from a seep, the dust particles tend to leave the surface area perpendicularly, with directions spread by only *full-width-at-half-maximum* FWHM $= 19^\circ$ about nominal. Gas outflow, in contrast, is less confined, with a FWHM of $\sim 90^\circ$.[22]

2.3 The driving force: evaporation of ices

Whipple's old idea of a spherical snowball warmed by sunlight is pretty much redundant now that comets are found to be dark and covered by a crust. However, the main idea of dust particles being dragged along by water vapor is alive and kicking, because

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[21] J.-F. Crifo, A. V. Rodionov, K. Szego and M. Fulle, Challenging a paradigm: do we need active and inactive areas to account for near-nuclear jet activity? *Earth, Moon, Planets* **90** (2002), 227–238.

[22] H. Kohl, K. Kölzer, E. Grün and K. Thiel, Dust-particle acceleration near simulated cometary surfaces: experimental results. In *Asteroids Comets Meteors III*, Uppsala, 1989 pp. 367–371.

it is a way to accelerate the grains. When ices evaporate, the outflowing vapor can push the grains.

Ices are small molecules that are solid at low temperature but evaporate at room temperature. The ice of comets is a mean cocktail of 79% water (H_2O), 13% carbon monoxide (CO), 2.8% dry ice (CO_2), 3.0% formaldehyde (H_2CO), 1.0% methanol (H_3COH), 1.2% ammonia (NH_3), and 0.08% hydrogen cyanide (HCN), amongst others. Of all these ices, water is the least volatile because it is most strongly bonded. All the other ices are trapped in a matrix of water ice. As a result, it is the evaporation of the water ice that drives much of the outgassing of comets.

The carbon monoxide molecule has such a low sublimation temperature that it is very unexpected to find CO in a comet. It should all have evaporated long ago. We now know that CO molecules are caged in the water ice and thus prevented by the strongly bonded structure of water molecules from evaporating until much higher temperatures. This is possible, because the water ice is not crystalline as in the snowflakes on Earth, but in a disordered amorphous form. Like window glass is an amorphous form of the mountain crystals of quartz (with impurities of soda and lime). When ice crystallizes into snowflakes, all the impurities are expelled. Amorphous water ice is a very interesting material and when I first came to the NASA Ames Research Center in California in 1993, I spent many hours probing its peculiar structure with a transmission electron microscope in experiments with David F. Blake (Fig. 2.6). We found that the amorphous water frost of interstellar grains, formed at temperatures $T < 15\,\mathrm{K}$, can rearrange into a more open structure when it is warmed a few tens of degrees. At even higher temperatures, this amorphous ice starts to become soft and turn into a glass, a viscous liquid, much like window glass when heated in an oven. This property of the ice was known before, but never thought to be important because the ice also quickly crystallizes into small solid cubic ice crystals. However, David and I found that most ice in the thin films we studied never crystallized completely and the ice continued to flow until all of it turned into the hexagonal ice crystals of snow at a much higher temperature! In the microscope, we saw that the ice retracted from the hydrophobic amorphous carbon substrate and formed little droplets as soon as its viscosity decreased. This exotic "restrained" amorphous form of (still very viscous) *liquid* water may occur naturally in comets.[23]

The heat of the Sun evaporates the water, increasingly as the comet approaches the Sun. The distance to the Sun is called "*r*" (from heliocentric *radius*) throughout this

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[23] P. Jenniskens and D. F. Blake, Structural transitions in amorphous water ice and astrophysical implications. *Science* **265** (1994), 753–756; D. F. Blake and P. Jenniskens, The ice of life. *Sci. Am.* August (2001), 2–7; P. Jenniskens and D. F. Blake, Crystallization of amorphous water ice in the solar system. *Astrophys. J.* **473** (1996), 1104–1113.

Fig. 2.6 Electron microscopy studies of the ice of comets. Author with Dr. David F. Blake (seated). Photo: NASA Ames Research Center.

book, usually measured to the center of mass of the solar system rather than the center of the Sun alone. That center of mass is inside the Sun (Chapter 13). This distance is expressed in terms of *Astronomical Units* = 149 597 870.691 km, approximately the distance between Earth and the Sun.[24] The Earth is always close to $r = 1$ AU, to within ±0.02 AU on account of a slightly elliptical orbit.

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[24] The formal definition of *Astronomical Unit* is the radius of an unperturbed circular orbit that a massless body would revolve about the Sun in $2(\pi)/k$ d (i.e., 365.256 89... d), where k is defined as the Gaussian constant exactly equal to 0.017 202 098 95. Since an AU is based on the radius of a circular orbit, 1 AU is slightly less than the average distance between the Earth and the Sun.

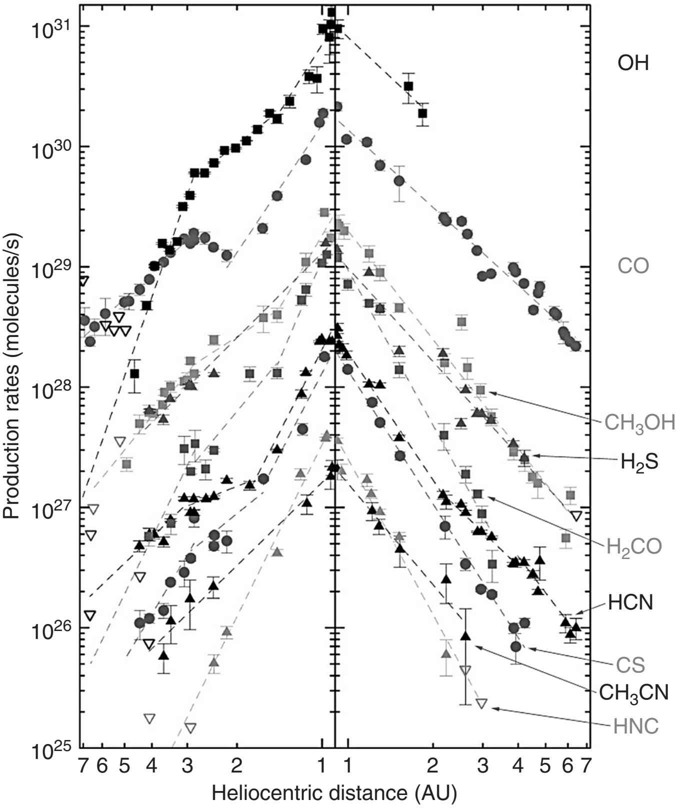

Fig. 2.7 The amount of ices lost from comet Hale–Bopp per second as a function of the distance from the Sun. "OH" marks the sublimation of water ice, CO the sublimation of carbon monoxide, and "CH_3OH" the sublimation of methanol (methyl alcohol). Image by Nicolas Biver, Meudon Observatory.

When a comet moves closer to the Sun, the comet nucleus surface will warm to a temperature of about: $T = 300/\sqrt{r}$ (with r in AU) degrees Kelvin. When water ice is exposed to the vacuum of space at temperatures above 175 K (at 3 AU), it will evaporate without melting, a process called *sublimation*, just as does the "dry ice" from a fire extinguisher. Before the water ice sublimates, less volatile molecules are lost from its matrix, fizzing out like the pop in soda. As expected, the first to go is carbon monoxide (CO, Fig. 2.7) and other weakly bonded compounds. For that reason, CO is often seen in comets as far out as 7 AU from the Sun ($T_s \sim 115$ K), beyond the orbit of Jupiter.

Only when the temperature of the ice rises above the sublimation temperature of water ice at distances less than 3 AU, in the case of Hale–Bopp when the comet crossed the asteroid belt, is water observed to leave the comet and to quickly fall apart into $H_2O \rightarrow H + OH$ (Fig. 2.7).

2.4 How to lift the grains from the comet surface

There are a number of ways for comets to lose solid particles. Whipple envisioned the dust particles to be imbedded in the flow of water vapor and calculated at what final speed those dust particles emerge from the water vapor jets (after taking into account the speed lost from escaping the gravity of the comet). That formula was based on the concept that a gas flow colliding with a particle will push it, in much the same way as a meteoroid entering the Earth's atmosphere is slowed down by collisions with air molecules. Indeed, Whipple's equation originated from his work on meteor trajectories in the atmosphere.

Whipple's equation for meteoroid ejection (Appendix A) is still used today, albeit with some modifications. There are a number of different formulas around, each taking into account certain aspects not considered by Whipple. For example, Whipple did not consider the presence of the jets that cause energy to be lost from a smaller surface area than where it is absorbed, the adiabatic expansion of the vapor when it flows into space, nor did he consider nonspherical grains that may sail more efficiently in the water vapor wind, or the delayed evaporation of ice that can propel the grains like a rocket. All these effects can potentially change the outcome of the ejection process dramatically.

One of the latest incarnations by Jean-François Crifo and Alex V. Rodionov[25] (the *Crifo ejection model*) was developed for the interpretation of comet images and is used in the meteor storm prediction software developed in the Ph.D. thesis work of Jerémié Vaubaillon, results of which are presented throughout this book. The software was developed in collaboration with thesis advisors François Colas and William Thuillot at the recently founded *Institut de Mécanique Céleste et de Calcul des Ephemerides* (IMCCE) in Paris, France, and was applied during Jerémié's postdoctoral stay at the SETI Institute in late 2004, where he worked with the author during the writing of this book.

Those modifications are important, but only insofar as they can be validated by observations. According to Whipple's formula, a typical +3 magnitude Leonid meteoroid ejected at perihelion would give a speed of $V_{\mathrm{ej}} = 28.5\,\mathrm{m/s}$, which is 103 km/h.[26] Crifo's main modification is the inclusion that only a small fraction of the surface ejects meteoroids, resulting in an ejection speed of: $V_{\mathrm{ej}} \leq 12.8\,\mathrm{m/s}$ if 24% is active, or $V_{\mathrm{ej}} \leq 14.9\,\mathrm{m/s}$ if only 4% of the surface is active. This would mean a meteor shower at least half as wide.

It is important to realize that the coupling between gas and dust is poor and the ultimate speed of a meteoroid is only a small fraction of the outflow speed of the gas. The smaller particles are more efficiently accelerated than the large ones. In the case of comet C/Hale–Bopp, water vapor flowed out at 1200 m/s at $r = 0.9$ AU, decreased to

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[25] J.-F. Crifo and A. V. Rodinov, The dependence of the circumnuclear coma structure on the properties of the nucleus. *Icarus* **127** (1997), 319–353.

[26] For a Leonid of $M = 0.008$ g and $\rho = 0.7\,\mathrm{g/cm^3}$, Tempel–Tuttle's diameter $D_{\mathrm{c}} = 3.5$ km, $\rho_{\mathrm{c}} = 0.5\,\mathrm{g/cm^3}$, $\Lambda = 1$, at a distance $r = 0.976$ AU from the Sun.

500 m/s at $r = 6$ AU, about a hundred times larger than the outflow speed of large meteoroids. Moreover, when the gas flows out more violently, it drags along more dust. While the gas production rate fell off with an r^{-2} power law away from the Sun (Fig. 2.5), the dust production rate of comet 1P/Halley fell off with a steeper $r^{-3.0 \pm 0.7}$ power law. Most dust was ejected when the comet was closest to the Sun.[27]

The ejection speed of these meteoroids is mostly determined by the initial acceleration in pits or just above the comet surface. Although the interaction with the gas continues as far out as ~5 times the nucleus size, the water vapor loses most of its dragging force when it expands and becomes less dense only a few (tens of) meters above the surface of the comet.

In Whipple's picture, the grains are embedded in the ice and therefore, in a way, are already entrained in the gas flow when the water evaporates. We now know that comets are mostly dust with little ice (Chapter 15). In that case, the dust has to break from the rest of the comet before being dragged along in the vapor (the bonds between the grains have been eroded). More fragile material may be lost first, while more sturdy material may be lost in larger chunks that can fall back onto the surface of the comet.

Meteoroid fragmentation during and after ejection can also change the outcome. The main effect would be that small grains can have the lower ejection speed expected for the original larger grains. Indeed, fragmentation shortly after ejection is a common phenomenon.[28] When the Giotto satellite approached the nucleus of comet Halley, a large number of tiny attogram ($= 10^{-18}$ g) grains were discovered, thought to be the product of vigorous fragmentation of dust out to distances of 1 million km from the nucleus.[29] Larger grains often arrived in clusters. Also, the distribution of scattered sunlight from very small grains and the distribution of CO gas, presumably still evaporating from the fragmenting grains, were more persistent away from the comet nucleus than would be expected if there was no fragmentation.[30]

The reason for fragmentation is perhaps the continued evaporation of ice and the heating by sunlight. After ejection from the comet, the dust grains will first be under stress from the remaining ice turning into vapor, putting pressure on the walls of pores. Dark (absorbing) dust grains tend to warm to the point of sublimation in a few hours or less, evaporating any remaining ice before the particle has moved a few hundred kilometers from the surface. While dragged out by the vapor, the grains are repeatedly heated and cooled, while spinning in the bright sunlight. What remains after this process are the meteoroids that we see as meteors.

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[27] P. D. Singh, W. F. Huebner, R. D. D. Costa, S. J. C. Landaberry and J. A. de Freitas Pacheco, Gas and dust release rates and color of dust in comets P/Halley (1986 III), P/Giacobini–Zinner (1985 XIII), and P/Hartley–Good (1985 XVII). *Planet. Space Sci.* **45** (1997), 455–467.

[28] H. U. Keller, M. L. Marconi and N. Thomas, Hydrodynamic implications of particle fragmentation near cometary nuclei. *Astron. Astrophys.* **227** (1990), L1–L4.

[29] N. G. Utterback and J. Kissel, Attogram dust cloud a million kilometers from comet Halley. *Astron. J.* **100** (1990), 1315–1322.

[30] Eberhardt P., Krankovwsky D., Schulte W. *et al.*, The CO and N_2 abundance in comet P/Halley. *Astron. Astrophys.* **187** (1987), 481–484.

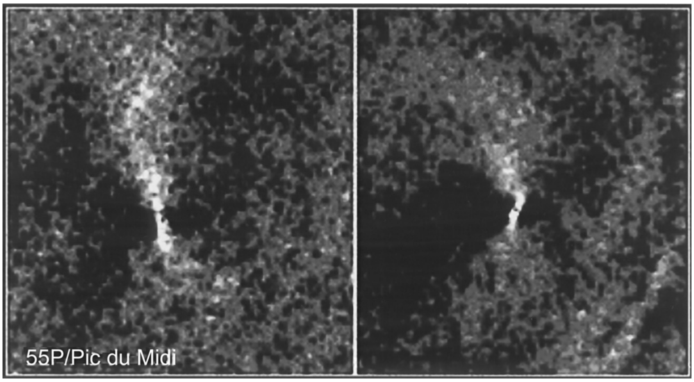

Fig. 2.8 The dust jets of comet 55P/Tempel–Tuttle the parent of the Leonid shower, by François Colas of IMCCE, taken at the Pic du Midi Observatory.[31]

After the vapor dissipates, dust continues to stream away from the nucleus into space, on its own independent orbit around the Sun. When the comet nucleus spins, a jet will point in different directions over one rotation, but the particles will continue to move outwards in nearly straight lines. This will cause the jet to have a corkscrew-shape (Fig. 2.8). The jet of Leonid parent 55P/Tempel–Tuttle in 1998 was located at a northern position on the nucleus at a small angle to the spin pole, judging from the small opening angle of the corkscrew motion. The comet is seen to spin with a period of 15.33 ± 0.02 h.[32] In comparison, 19P/Borrelly rotated with a period of 25.0 ± 0.5 h. The dust grains are ejected during daytime. When it is morning at the vent on the comet surface, the jet starts to sprout again and a new band of dust is deposited.

Water vapor can not drag along very large pieces. Whipple calculated that the *maximum sized* Leonid that can be lifted off the nucleus by water vapor drag (the particles having ejection speed of 0 m/s) would be about 19 cm in diameter, or some 2.7 kg in mass (Appendix A). Such a large fragment would cause a spectacular -11^{m} fireball, nearly as bright as a full the Moon and casting shadows. Instead Leonid fireballs as bright as -15^{m} have been reported during the recent Leonid storms.

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[31] Measured on January 30, 1998, by Jean Lecacheux, Eric Frappa, and François Colas of Pic du Midi observatory.

[32] *Ibid.*

3

The formation of meteoroid streams

Meteoroid streams in space used to be invisible, their existence illuminated only by the meteor showers they caused on Earth. Then, in 1983, *dust trails* were discovered in the orbit of short-period comets. Dust grains absorb visible light, warm up, and re-emit that energy as thermal emission in the mid-infrared.

My Alma Mater at *Leiden Observatory* was deeply involved in the interpretation of data from the monumental 1983 all-sky survey of heat emissions at the mid-infrared wavelengths of 12, 25, 60, and 100 μm by the *InfraRed Astronomical Satellite* (*IRAS*), a joint project of the USA, UK, and the Netherlands. The observatory had a vested interest in the topic of interstellar dust, with my professor, Harm Habing, being one of the leading investigators of IRAS. As in so many astronomical institutes, meteor studies were delegated to amateurs. I was such an amateur, joining the ranks of the Dutch Meteor Society two years earlier.

When the news spread that the images from IRAS showed dust trails in the path of comets, I immediately suspected a link with meteor outbursts.[1] It was the excellent 1986 report by *Mark Sykes* and coworkers, with details of the width of the trails and estimates of the sizes of the dust grain,[2] that first alerted me to the trails, although the discovery was made by *John Davies* a few years earlier and published in a paper that discussed other things as well.[3]

John Davies, a scientist involved with the IRAS moving object project at the University of Hawai'i, recalls how he discovered the trails in the images of the IRAS satellite: "One day in August, 1983 the fast moving object detection software seemed to find a number of 'asteroids' all in the same patch of sky. None of these looked right and they could not have been a single object being detected several times as the motion would have been too erratic to be real, so I did not worry too much about them. However, to my surprise the next day several more

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[1] P. Jenniskens, Stofsporen. *Radiant, J. DMS* **9** (1987), 73–74.

[2] M. V. Sykes, L. A. Lebofsky, D. M. Hunten and F. Low, The discovery of dust trails in the orbits of periodic comets. *Science* **232** (1986), 1115–1117.

[3] J. K. Davies, S. F. Green, A. J. Meadows, B. C. Stewart and H. H. Aumann, The IRAS fast-moving object search. *Nature* **309** (1984), 315–319.

appeared in a very similar region. This went on for several more days and eventually I tried plotting all the positions onto a map of the sky. The result was amazing, all the objects seemed to lie on a straight line! A closer look at the positions revealed that the structure pointed straight at the position of comet 10P/Tempel 2," from which the dust grains appeared to originate. John predicted that the trails would move along with the comet in projection on the sky, and saw that to be true when IRAS returned to the area a few days later.

Fig. 3.1 shows a compilation of IRAS images. Most of the emission from the zodiacal light in the center of the image has been removed to bring out the more subtle structures. The horizontal bands that remain after removing a smooth zodiacal light component are due to asteroidal dust grains in what are called the *zodiacal dust bands*. The irregular wisps above and below are the interstellar clouds of our galaxy seen from a great distance.

The comet dust trails are the thin lines stretching across the sky. A particularly bright one emanates from the position of comet 10P/Tempel 2, marked by an arrow. Another belongs to comet 2P/Encke, associated with the Taurids (just above the ecliptic plane in the center of the image). A third dust trail is from comet 7P/Pons–Winnecke, parent of the June Bootids.

What peaked my curiosity was that Davies and Sykes rejected the notion that dust trails could be responsible for meteor showers, because they could not identify any. Comet Encke was a known source of meteor showers, but the Encke trail was much more confined in space and distinct from the Taurid showers. Instead of days or months, it would take Earth only 1.4 h to cross the dust trail, measuring no more than 150 000 km (~0.001 AU) instead of ~0.44 × 0.05 AU for the Orionids, for example. As Sykes wrote:[4] *Meteoroid streams are qualitatively very different from their trail counterparts in that they are far more dynamically evolved, are spread out over a vastly greater volume, and often have mean orbits whose nodes are significantly separated from their parents*. Sykes and Walker calculated that the dust trails were so dense that an observer would see more than 10 000 meteors per second (!) if Earth were to cross the dust trail near the position of comet 10P/Tempel 2. From the reported dust density of $\sim 3 \times 10^{-16}\,\mathrm{cm}^{-3}$, however, I calculated a zenith hourly rate of ZHR ~140 000, or at best ≤ 40 meteors per second were these to hit Earth at the speed of Draconid meteors.

I knew that there were meteor showers that lasted only ~1.4 h. In fact, they were more common than generally believed. In 1985, there were outbursts of the August *β-Hydrusids*, the October *Draconids*, and the November *α-Monocerotids*, while in 1986 there were *κ-Pavonids* in July, September *Aurigids*, and a burst of December *Ursids*.

As an undergraduate student, I set out to collect as much information about such meteor outbursts as I could find to establish the link between meteor outbursts and comet dust trails, in the process attempting to define what is the normal annual shower

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[4] M. V. Sykes, D. J. Lien and R. G. Walker, The Tempel 2 dust trail. *Icarus* **86** (1990), 236–247; M. V. Sykes and R. G. Walker, Cometary dust trails. I Survey. *Icarus* **95** (1992), 180–210.

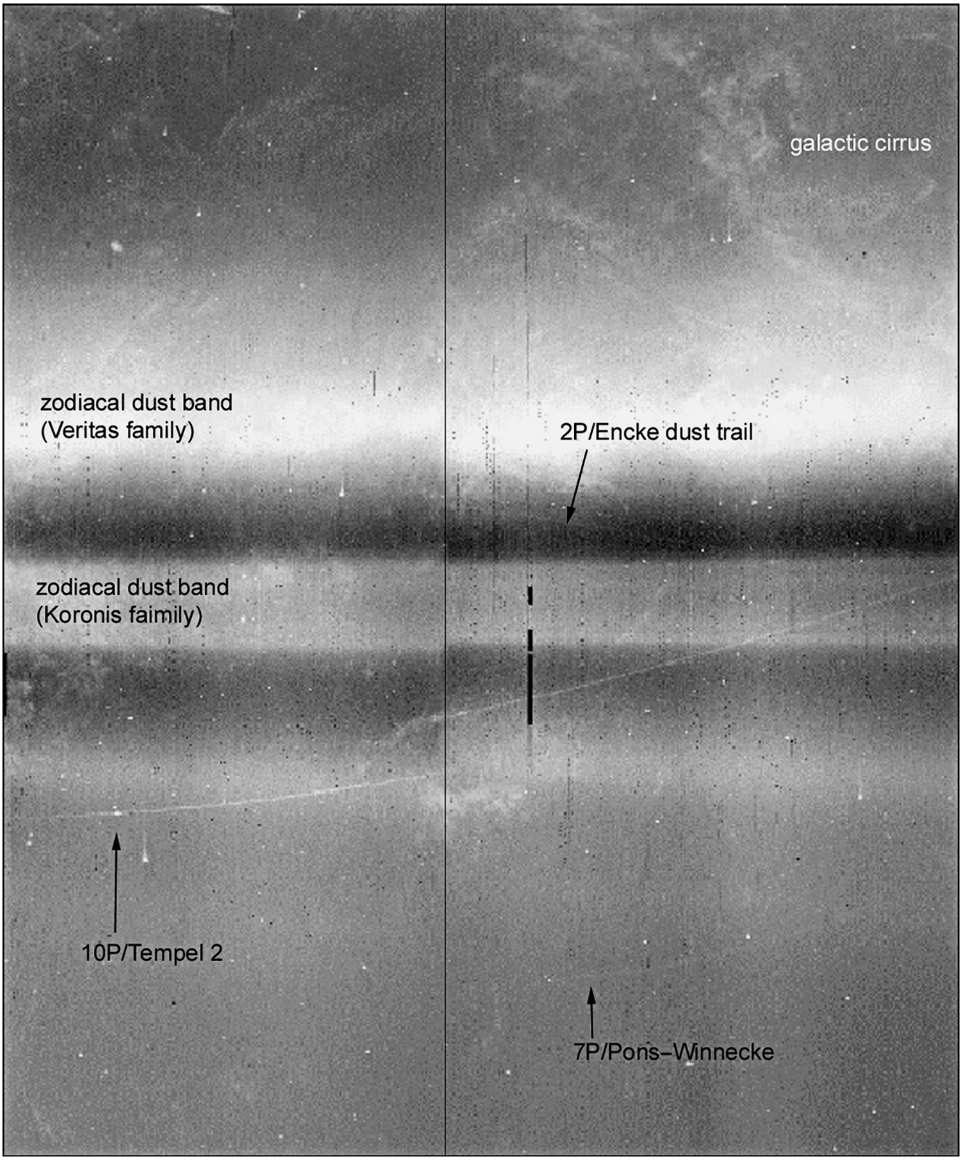

Fig. 3.1 Dust trails in IRAS images. A 40° × 50° area of the sky in a mosaic of 25 and 60 μm mid-infrared HCON-1 IRAS images, centered on the ecliptic plane. Dust trails of 2P/Encke, 10P/Tempel 2, and 7P/Pons–Winnecke are marked. Image courtesy of Mark Sykes, University of Arizona, and William Reach, IPAC.

activity.[5] At the same time, Slovak meteor astronomer *Lubor Kresák* (1927–1994) thought the same and first published papers discussing this connection in 1992 and 1993.[6]

While a student at Charles University in Prague, Kresák had observed the 1946 Draconid storm from Skalnaté Pleso Observatory in the northern mountains of Slovakia on the Polish border.[7] He continued to graduate in 1951 on a thesis "Structure, mass, and age of the comet Halley meteoroid stream." After his graduation, he worked at Skalnaté Pleso until 1955, where he discovered comets 41P/Tuttle–Giacobini–Kresák and C/1954 M_2 (Kresák–Peltier). He then worked at the Astronomical Institute of the Slovak Academy of Sciences in Bratislava on the dynamics of comets and asteroids and on meteor showers. He is remembered for insightful tools and diagrams to address the dynamical interpretation of observations.[8] His final work on attempting to link meteor showers with comet dust trails put a crown on a very rich and fruitful career covering both comets and meteor showers. Kresák died on January 20, 1994.

Later that year, meteor astronomer Duncan Steel wrote: *The relationship between these trails and the streams observed as meteor showers at the Earth is by no means clear at this stage*.[9] My inventory of annual shower activity based on visual observations of the Dutch Meteor Society (gathered by the Visual Section leader Rudolf Veltman) and the Western Australian Meteor Society (gathered by Jeff Wood) finally appeared in 1994,[10] and that of meteor outbursts and their relationship to IRAS dust trails in 1995.[11]

3.1 Comet coma and tail

Before discussing how comet dust trails are formed, let us first examine how the gas and smaller meteoroids of a comet move away from the nucleus. These make *tails* instead of trails (Fig. 3.2).

The *ion tail* of a comet is part of the remains of the evaporated ices. The vivid blue–green colour is a fluorescent molecular band emission from long-lived positively charged carbon-monoxide molecules (CO^+), after solar radiation knocked off an electron from CO molecules and thus created *ions*. The charged ions feel the Sun's magnetic field and are swept almost exactly in a direction away from the Sun along the magnetic field that emanates from Sun spots, distorted by the *solar wind* of charged

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[5] P. Jenniskens, Meteor stream activity profiles from naked eye counts. In *Asteroids, Comets, Meteors III*, ed. C.-I. Lagerkvist, H. Rickman, B. A. Lindblad and M. Lindgren. (Uppsala: Uppsala University, 1989), pp. 535–538.

[6] L. Kresák, Cometary dust trails and meteor storms. *Astron. Astrophys.* **279** (1993), 646–660.

[7] I. P. Williams, Lubor Kresák (1927–1994). *Quart. J. R. Astron. Soc.* **35** (1994), 579.

[8] A. Carusi and G. Valsecchi, In memoriam – Lubor Kresák. In *Asteroids, Comets, Meteors 1993: Proc. 160th Int. Astronomical Union*, ed. A. Milani *et al.*, (Dordrecht: Kluwer, 1994) pp. 75–76.

[9] D. Steel, Meteoroid streams. In *Asteroids, Comets, Meteors 1993: Proc. 160th Int. Astronomical Union*, ed. A. Milani *et al.*, (Dordrecht: Kluwer, 1994) pp. 111–126.

[10] P. Jenniskens, Meteor stream activity. I. Annual streams. *Astron. Astrophys.* **287** (1994), 990–1013.

[11] P. Jenniskens, Meteor stream activity II. Meteor outbursts. *Astron. Astrophys.* **295** (1995), 206–235.

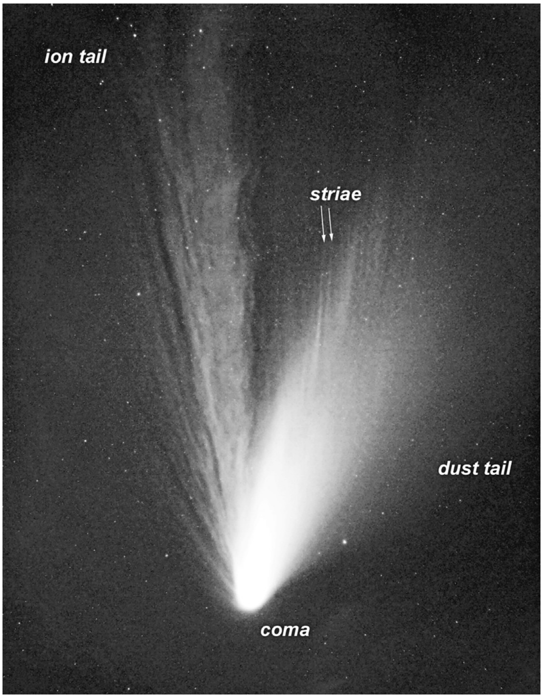

Fig. 3.2 Comet C/Hale–Bopp in a photo by Wei-Hao Wang (Institute for Astronomy at the University of Hawai'i). The photo was taken from Taiwan, at 20:38 UT on March 9, 1997, 22.3 d before perihelion.

particles that sweep past the comet at 500 km/s. The resulting filamentary structures can change in minutes. When the comet travels through magnetic polarization reversals, there are abrupt ion tail disconnections.

Neutral gas molecules (and large dust grains) hang around the nucleus to form a *coma*, rich in green CN and C_2 molecular band emissions. The latter do not originate from ices, but from the organic matter in the meteoroids.

The *dust tail* is the ensemble of all the small solid particles that are strongly affected by the solar radiation pressure. The tail is made visible mainly by scattered sun light, due to dust particles that are comparable to or smaller in size than the wavelength of light, that is up to about 10 µm. My other thesis advisor at Leiden University, Professor *J. Mayo Greenberg*, used to demonstrate how efficiently small particles scatter light by smoking a cigarette into the light of an overhead projector. A puff of smoke can scatter away so much light that it darkens the screen. In contrast, a piece of chalk leaves most of the light untouched despite having much more mass. Despite his love for light scattering, Mayo despised cigarettes and performed this trick only reluctantly, often to demonstrate how the comet surface can be dark because of the fine-grained and fluffy morphology of the surface materials, fallen back meteroids, by scattering light inwards.

3.2 Radiation pressure

Once ejected, the trajectories of these grains are determined by their ejection speed *and* by the momentum carried by the Sun's radiation. The force of impact by absorption or scattering of a light particle (a massless photon) is very small, but there are so many light particles that a small meteoroid can feel a strong push away from the Sun. This is called *radiation pressure*. Radiation pressure, being a factor β times as strong as gravity, lowers the pull from gravity by a factor $1-\beta$.

Heavy meteoroids are more difficult to blow off course. Hence meteoroid mass and the parameter β are often used interchangeably. However, it matters whether the grains are compact and spherical or fluffy, perhaps fractal, in shape. For spherical grains of diameter d (cm) and density ρ (in g/cm^3) and radiation pressure efficiency Q_{pr}, the relationship is (masses $> 10^{-12}$ g):[12]

$$\beta = 1.148 \times 10^{-4}\, Q_{\mathrm{pr}}/\rho\, d \tag{3.1}$$

For even smaller grains (smaller than the wavelength of light), the absorption is not efficient and β drops off. The pressure efficiency includes the effect of *albedo*, which is the percentage of light absorbed. Better absorbing grains have a peak $\beta_{\mathrm{max}} > 1$, for example $\beta_{\mathrm{max}} = 1.8$ for iron grains, and $\beta_{\mathrm{max}} > 5$ for graphite, while very transparent particles have $\beta_{\mathrm{max}} \sim 0$. Because of all this, the ejection speeds of dust particles need to be calibrated by observations. It is found that the meteoroids in comet tails tend to have $\beta_{\mathrm{max}} \sim 2.5$.

If the solar radiation pushes just as hard outward as the solar gravity pulls the particle inwards, then $\beta = 1.0$. At that moment, there is no net force and the particles continue to move on a straight line out of the solar system. Comet dust tail particles have β in the range 0.01–2.5, while dust trails and meteoroid streams typically have $\beta \sim 0.001$.

Those heavier particles follow curved elliptical orbits in the same plane as the comet, forming a thin sheet. When the Earth crosses the orbital plane of the comet it is possible for large dust grains, ejected at some prior time, to be in projection against the sky in front of the comet nucleus. The result is a spike pointing in the direction of the Sun. This is called the *antitail* of the comet (Fig. 3.3). Some amount of spreading of large grains is needed to get an antitail and that usually means that antitails are best seen after the comet has passed perihelion, permitting the dust moving on different orbits to separate far enough from the comet.

The apparent trajectories of the meteoroids after ejection from the comet can be calculated, assuming different levels of radiation pressure. Fig. 3.4 shows a *synchrone/syndyne diagram*. The curved dashed lines mark the position of a cloud of particles with

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[12] From the ratio of the force of radiation pressure and the force of gravity: $\beta = (Q_{\mathrm{pr}}\, L_{\odot} A/4\,\pi\, c)/G\, M_{\odot} M$, where $M_{\odot}$ and $L_{\odot}$ are the Sun's mass and total energy emitted per second, A is the projected cross-sectional area of the particles, G is the gravitational constant, c is the speed of light, and M is the mass of the metoroid. From: Z. Sekanina, M. S. Hanner, E. K. Jessbergr and M. N. Fomenkova, Cometary dust. In *Interplanetary Dust*, ed. E. Grün, B. Å. S. Gustafson, S. F. Dermott and H. Fechtig. (Berlin: Springer, 2001), pp. 95–161.

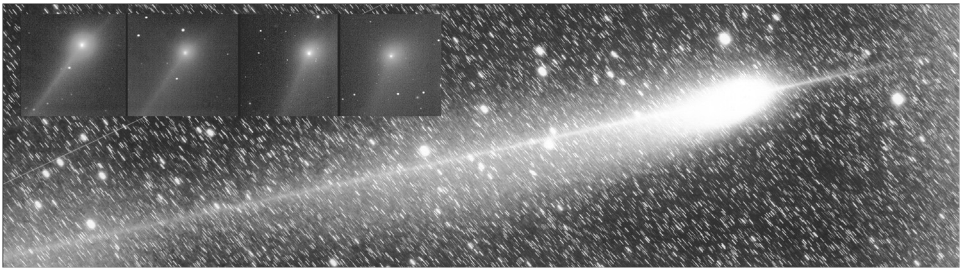

Fig. 3.3 The dust tail is a thin sheet as shown by Hale–Bopp when Earth crossed the plane of the comet's orbit on January 5, 1998 (Photo with the ESO 1.4 m Schmidt Telescope by Guido Pizarro). The inset shows the antitail of comet C/1995 Q_1 (Bradfield) as seen from slightly different perspectives while crossing the comet orbital plane, in images taken by Allessandro Dimai of the Associazione Astronomica Cortina, Obs. "Helmut Ullrich" at Col Drusciè – Italy, on September 30 (03:25 UT), October 04 (03:40 UT and 04:06 UT), and October 21 (04:06 UT).

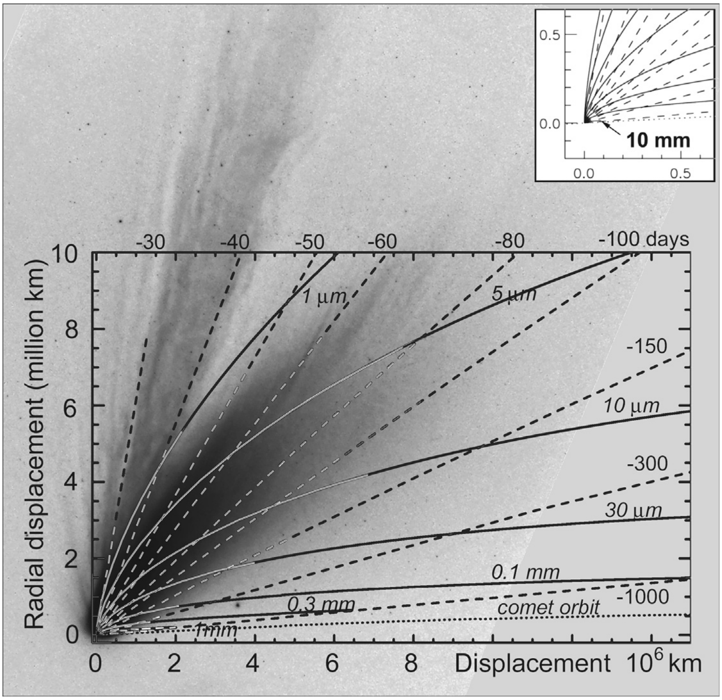

Fig. 3.4 Synchrones and syndynes overlaying the image of comet Hale–Bopp. The Sun is towards the bottom of the graph, the comet moves from right to left along the dotted line. Synchrone and syndyne lines show the position of dust grains ejected at different times for grains of different size, respectively, as calculated by Marco Fulle of Trieste Observatory, Italy. The time of ejection is in days prior to perihelion. The large mm–cm sized grains are very close to the comet nucleus and in the orbit of the comet (inset).

different β ejected at *the same time* and observed a while later. This line is called a *synchrone* (from the Greek word *chronos* = time, as in "chronological"). Synchrones become visible as dust streamers when there is a sudden brief outburst of comet activity. Comet Halley had at least six such streamers.[13] Banded rectilinear structures in the dust tail, separated from the nucleus, are called *striae*, and are caused by large dust particles that fell apart into innumerably more tiny dust particles a short time after ejection.[14] Those dust particles are then pushed outward, more so for finer grains. As a result, this swarm of particles spreads out into elongated stripes along synchrones.

The curved solid lines in Fig. 3.4 are the position of particles of *the same* β (or forces, proportional to mass) ejected at different times. Such a line is called a *syndyne* or more correctly *syndyname* (from the Greek word *dunamis* = power; the same root as for the English words dynamite and dynamo). The graph of syndynes and synchrones in the coordinate system of the comet show the age and mass of the particles at any position in the comet dust trail. *M. L. Finson* and *R. F. Probstein* developed a method using syndynes and synchrones to calculate the distribution of dust in the tail of a comet using the approach of adding the contributions from superimposed uniformly expanding shells, later used extensively and improved by Zdenek Sekanina, Marco Fulle, and others.[15]

3.3 The formation of dust trails

Comets do not leave the large meteoroids behind like a bar of soap in water. They initially move away from the comet only slowly (Fig. 3.3) and then spread quite dramatically in the form of a dust trail after one revolution. The formation of such structures was first described, in a manner, in the nineteenth century, notably as early as 1877 by the Russian astronomer *Theodor Brédikhine* of Moscow.[16] He was a very active and bold astronomer, responsible for introducing the names "synchrone" and "syndyne," but he also pursued many incorrect ideas. Based on the misconception that comet antitails were ejecta towards the Sun, Brédikhine correctly proposed that meteoroid streams were formed from nuclear ejections towards the Sun. To account for the antitails, he assumed that the grains were ejected with high enough speeds to populate a sheet of dust with elliptic, parabolic, and hyperbolic orbits.

Shortly after Fred Whipple calculated actual ejection speeds, which were much smaller, *Miroslav Plavec* (the Technical University, Prague) first described the

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[13] P. Lamy, Ground-based observations of the dust emission from comet Halley. *Adv. Space Res.* **5** (1986), 317–323; K. Beisser and H. Boehnhardt, Evidence for the nucleus rotation in streamer patterns of comet Halley's dust trail. *Astron. Space Sci.* **139** (1987), 5–12.

[14] Z. Sekanina and J. A. Farell, Two dust populations of particle fragments in the striated tail of comet Mrkos 1957 V. *Astron. J.* **87** (1982), 1836–1853.

[15] M. L. Finson and R. F. Probstein, A theory of dust comets. I. Model and equations. *Astrophys. J.* **154** (1968), 327–352.

[16] From: C. P. Olivier, *Meteors* (Baltimore: Williams and Wilkins, 1925) pp. 207–211; Th. Brédikhine, Sur l'origine des étoiles filantes. *Bull. Soc. Imp. Nat. Moscou* 1888; Th. Brédikhine, *Bull. l'Acad. Imp. Sci. St. Petersbourg* **17** (1902), 181; R. Jägermann, *Professor Dr. Th. Bredichin's Mechanische Untersuchungen über Cometenformen*. (St. Petersburg: Voss, 1903).

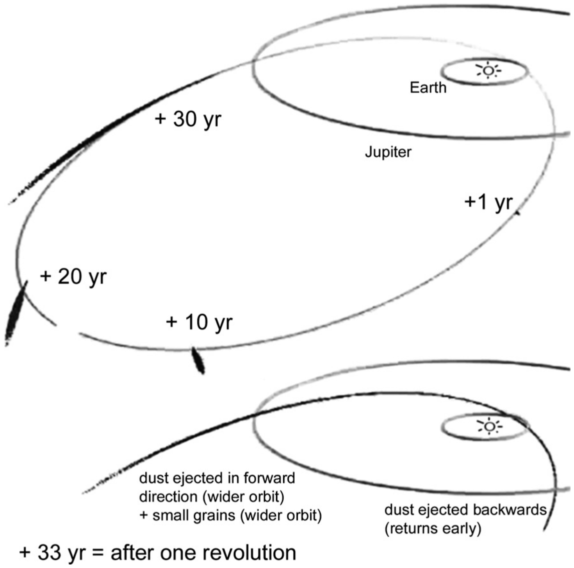

Fig. 3.5 Formation of a dust trail from dust ejected by comet 55P/Tempel–Tuttle, the parent of the Leonid shower, as calculated by Jérémie Vaubaillon, IMCCE.

formation of dust trails correctly as a result of slightly different orbital periods between the dust and the comet.[17] Hence, dust trails had been predicted to exist before they were first detected in space by IRAS.

Dust trails simply result from differences in the orbital period caused by ejection velocity and radiation pressure. The formation of a comet dust trail is illustrated in Fig. 3.5, which is a computation of the trajectory of 50 000 meteoroids ejected from comet 55P/Tempel–Tuttle in the year 1767. This figure from the Ph.D. thesis of Jérémie Vaubaillon shows nicely how the dust initially is a clump (a short dust *tail*) near the nucleus of the comet and only starts to spread out significantly when the dust arrives at the furthest point from the Sun. At this "aphelion," everything happens in slow-motion.

Most spreading along the comet orbit is established on the inward leg. That is also when planets influence meteoroids differently in different parts of the trail.

There is a 1:1 relationship between the conditions of ejection (and radiation pressure) and the final place of each particle in the dust trail (Fig. 3.5). The particles that were slowed down by ejection (or the larger particles that were pushed outward least by radiation pressure) will have the shortest orbit and return first, while the rest will follow later after completing a longer orbit. Under certain restrictions, the change in the meteoroid orbit and the subsequent dispersion of the dust can be expressed in analytical form (Appendix B).

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[17] M. Plavec, A classification of the meteor streams. *Bull. Astron. Inst. Czechoslov.* **5** (1954), 15–21; M. Plavec, Ejection theory of the meteor shower formation I. Orbit of an ejected meteor. *Bull. Astron. Inst. Czechoslov.* **6** (1955), 20–26; M. Plavec, On the origin and early stages of meteor streams. *Ceskosl. Akad. ved. Astr. Ústav Publ.* **30** (1957), 93 (see *Nature* (1957) **179**, 1063).

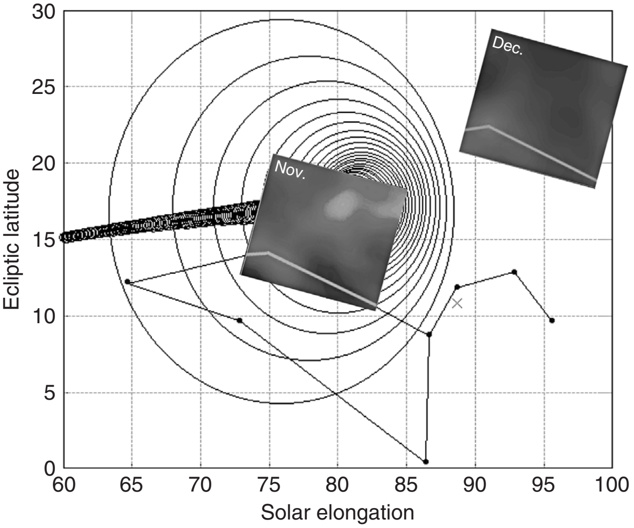

Fig. 3.6 The dust trail of comet 55P/Tempel–Tuttle in scattered sunlight in the direction of the approaching Leonid meteoroids. Results by Ryosuke Nakamura *et al.*[18]

Kresák[19] recognized that the smaller particles have the highest radiation pressure and will end up lagging the comet most. For that reason, meteor storms coming long after the passage of the comet are expected to consist of fainter meteors.

Indeed, Sykes and coworkers analyzed the eight dust trails detected by IRAS and found that they extended mostly behind the comet. The spreading along the comet orbit implied particle sizes of about 1 mm. Particles in front of the comet needed to be at least 6 mm in size,[20] because solar radiation pressure would delay the meteoroids to arrive after the comet if they were smaller. When hitting Earth's atmosphere slowly, 6 mm sized meteoroids cause a meteor of $+4.5^m$ in a typical slow collision, while a fast collision would result in a bright $+0.2^m$ meteor!

The grains were dark, their temperature implying that only 5% of light reflected back. The first optical detection of comet dust trails from scattered sunlight (the way we see the small particles in comet tails) was made by looking along the dust trail of comet 55P/Tempel–Tuttle at the time of the 1998 Leonid encounter. In setting up a coordinated observing campaign, I found that researchers at the University of Kobe in Japan had the expertise to do this experiment. Astronomer *Ryosuke Nakamura* and coworkers peeled away the light of stars, airglow, and zodiacal light from CCD frames taken at Hawai'i, to find a faint diffuse glow at the expected position of the

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[18] R. Nakamura, Y. Fum, M. Ishiguro *et al.*, The discovery of a faint glow of scattered sunlight from the dust trail of the Leonid parent comet 55P/Tempel–Tuttle. *Astrophys. J.* **540** (2000), 1172–1176.

[19] L. Kresák, Orbital evolution of the dust streams released from comets. *Bull. Astron. Instit. Czechoslov.* **27** (1976), 35–46.

[20] M. V. Sykes, L. A. Lebofsky, D. M. Hunten and F. Low, The discovery of dust trails in the orbits of periodic comets. *Science* **232** (1986), 1115–1117; M. V. Sykes, D. J. Lien and R. G. Walker, The Tempel 2 dust trail. *Icarus* **86** (1990), 236–247; M. V. Sykes and R. G. Walker, Cometary dust trails. I – Survey. *Icarus* **95** (1992), 180–210.

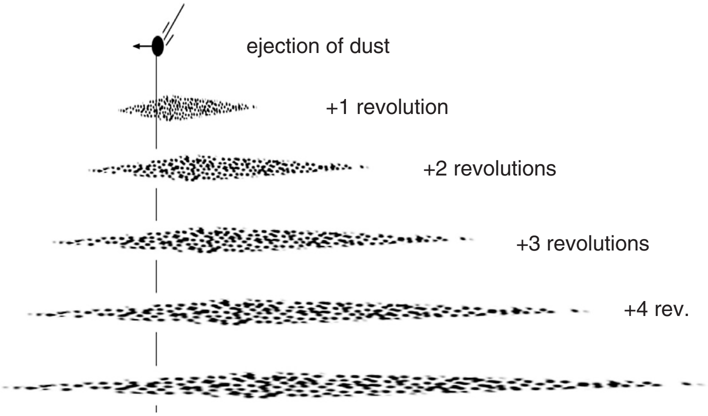

Fig. 3.7 **Dispersion of dust** in subsequent revolutions.

approaching meteoroids (Fig. 3.6). The November, 1998 image shows the scattered light from the approaching Leonid meteoroids (wire structure), while the December image (off-set) shows the absence of this emission a month later.

The first side view of a dust trail in scattered sunlight was obtained on February 14, 2002, by *Masateru Ishiguro* at Kiso Observatory.[21] It originated from the short-period comet 22P/Kopff, which was located at 3 AU from the Sun at that time, too far to detect an infrared signature.

If the orbital period of each meteoroid remains unchanged, the dust will continue to spread in the direction along the orbit of the comet (Fig. 3.7). The dust trail will increase in length proportionally to the number of revolutions, because the delays from each wider orbit add up. *Zdenek Sekanina* used this in an early attempt to trace meteor storms seen a certain time following the passage of a comet to the episode of ejection in the past.[22]

Finally, meteor storms do not get broader with age: the dust trails do not spread perpendicularly, because each particle ejected at a given point will return to that point if the orbit is not changed. Even if the orbit is changed by perturbations of the planets, those changes tend to be the same for all meteoroids in a cross section of the trail. As a result, the trail can get stretched, but will not broaden. Because of that, all meteor storms of a given stream tend to have much the same duration, even old dust trails.

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[21] M. Ishiguro, J.-I. Watanabe, F. Usui *et al.*, First detection of an optical dust trail along the orbit of 22P/Kopff. *Astrophys. J. Lett.* **572** (2002), L117–L120.

[22] Z. Sekanina, Meteoric storms and formation of meteor streams. In *Asteroids, Comets, Meteoric Matter*, ed. C. Cristescu, W. J. Klepczynski and B. Millet (Bucharest: Ed. Acad. Republicii Soc., 1975), pp. 239–267.

4

Meteors from meteoroid impacts on Earth

In the fall of 1798, University of Göttingen students *Johann Friedrich Benzenberg* and *Heinrich Wilhelm Brandes* set out to prove new ideas about the nature of meteors. In 1714, Edmund Halley had challenged Aristotle by suggesting that fireballs are not slow burning terrestrial vapors but solid objects entering Earth's atmosphere at high speed, only later to rescind. Ernst Chladni first reasoned that opinion most convincingly in 1794.

Between September 11 and November 4, Benzenberg and Brandes observed 22 meteors simultaneously from two locations 15 km apart.[1] By teaming up in this manner, each meteor was seen from two different perspectives, against a different background of stars. Comparing star charts, they noticed to their surprise and frustration, that the parallax was much less than expected, which meant that the meteors had to be further away and above the lower layers of the atmosphere that cause the weather.[2] This was a spectacular result! Despite the short baseline, their measured end heights were in the correct range between 35 and 126 km altitude, and they found the meteors traveling at correct speeds of some hundred thousand kilometers per hour (~28 km/s). Unfortunately, due to measurement errors, some solutions gave upward going trajectories, and it took a re-analysis, more triangulations, and another forty years, before it was accepted that meteoroids are solid bodies that come with great speed from outside Earth's atmosphere.

4.1 How dust trails manifest at Earth

The meteoroids in a stream move on nearly parallel trajectories. Standing in the middle of it, warmly clothed in the scented night, with fog on your breath and staring at the sky, an observer on Earth sees all the meteoroids approach and, as soon as they hit the atmosphere, cause a shower of meteors to radiate from one point on the sky, called the *radiant*. TV addicts such as myself recognize the radiant as the direction

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[1] H.W. Brandes and J.F. Benzenberg, Versuche, die Entfernungen, die Geschwindigkeit und die Bahnen der Sternschnuppen zu bestimmen. *Ann. Phys.* **6** (1800), 224.

[2] C. Hoffmeister, Hundertfuenfzig Jahre Meteorforschung. *Sterne* **24** (1948), 33–37.

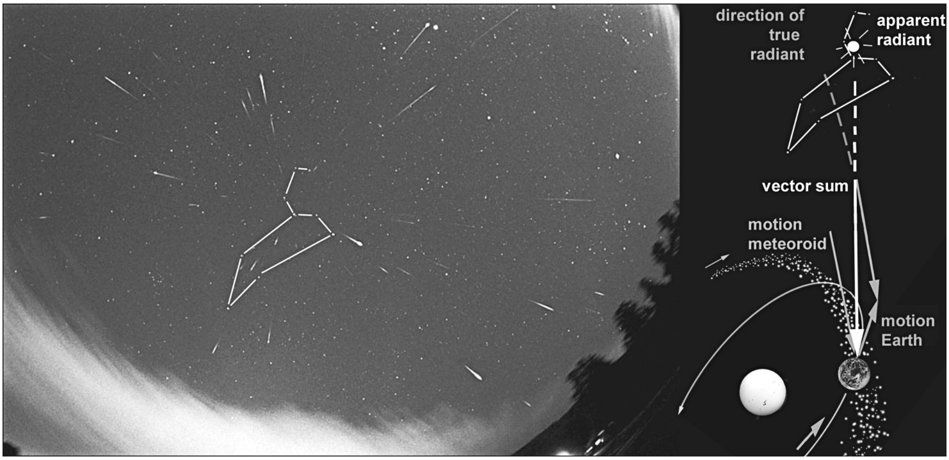

Fig. 4.1 The true and apparent radiant of the Leonid shower. The photo of the 2001 Leonid storm is by Ishiro Ohno of Kanazawa city, Japan. This image was made by combining photographs taken on ISO 800 film with a 15 mm F2.8 lens during 15:45–20:40 UT on November 18, 2001.

from which the stars are seen to approach in "10-forward." In that case, the radiant direction is purely determined by the direction of motion of the observer. For meteor showers, the radiant direction is a combination of the velocity of our spaceship (Earth) and that of the meteoroids.

We speak of the *velocity* of a meteor when both direction and magnitude matter, usually depicted by an arrow (vector) of given length and angle. *Speed* refers only to the magnitude of velocity, irrespective of direction. In order to find the radiant direction, one has to add the velocity arrows of both Earth and meteoroid. This is called a *vector sum*. In the case of the Leonids, Earth moves at about $V_E = 29.6$ km/s (ignoring the Earth's daily spin) in a direction slightly west from where the meteoroids are approaching at 41.1 km/s, both in a reference frame where the Sun is at rest. As a result, the apparent radiant in the head of Leo is slightly west from the "true radiant" (Fig. 4.1). The *true radiant* is the direction from where the meteoroids approach and the direction where Nakamura *et al*. discovered the diffuse glow of scattered sunlight (Chapter 3, Fig. 3.6).

When Leonid meteoroids fall in the gravity well of the Sun from far, they reach 41.1 km/s at Earth's orbit.[3] A collision with Earth creates a *geocentric velocity* (= from the perspective of the center of Earth) of: $V_g = 29.6 + 41.1 = 70.7$ km/s. This is strictly a vector sum, but here I ignore the small angle difference.

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[3] The total energy of a comet of mass M in the solar system is the sum of the kinetic and the potential energy: $E = \frac{1}{2}MV^2 - GM_{\odot}M/r$, where V is the comet's velocity and r is its distance to the Sun, with $M_{\odot}$ denoting the mass of the Sun and G being the gravitational constant. This energy remains constant: while the potential energy decreases, the kinetic energy increases proportionally.

Depending on the time of day and the position of the observer on the globe (away from Earth's center), the speed is modified slightly (aberration, up to ~0.4 km/s) by the Earth's spin. The speed is further modified by falling into the gravity well of Earth, causing the meteoroid to speed up by another 11.2 km/s before reaching an altitude of 100 km above Earth's surface. This increases the geocentric velocity of the meteor to the observed *atmospheric velocity* (V_∞, just prior to being slowed down by air collisions). The gain in speed is the result of a transfer of potential energy into kinetic energy and therefore the gain is calculated as a sum of squares: $V_\infty = \sqrt{(70.7^2 + 11.2^2)} = 71.6\,\mathrm{km/s}$.

The direction of V_g is called the *geocentric radiant*, and is expressed in equatorial coordinates of *Right Ascension* (R.A.) and *Declination* (Decl.). The gravity of Earth also changes the direction of the meteoroid motion, moving the radiant to an apparently higher position on the sky. This phenomenon is called *zenith attraction* and is more pronounced for slow meteors. A method for calculating the change in radiant and speed is given in Appendix B. The gravitational attraction of Earth also increases the area over which Earth sweeps up dust (and hence the rate of meteors) by about a factor $1 + V_\mathrm{E}^2/V_\mathrm{g}^2$,[4] while the observed rate of meteors, the "zenith hourly rate", relates to the actual dust density in the stream approximately as $\sim \mathrm{ZHR}/V_\mathrm{g}/V_\infty^{3.92}/(1 + V_\mathrm{E}^2/V_\mathrm{g}^2)$.[5] All radiants and speed mentioned in this book, unless specifically stated, are the geocentric radiant and speed, before the influence of zenith attraction.

Because Earth is always changing direction in its course around the Sun, the radiant moves from day to day. Despite William F. Denning's claims to the contrary in the early days of visual meteor shower observations, when he was the authority on the matter, radiants are not stationary. The change in direction of Earth's motion is 360° in 365.25 d, or about one degree each day. The position of the radiant changes accordingly. The Perseid shower radiant, as Denning himself showed for the first time, is in the constellation of Cassiopeia in early July and shifts towards Perseus in August, where the shower peaks, and then on into Camelopardalis (Fig. 4.2).[6]

The amount of radiant drift depends on the ecliptic latitude of the radiant and also on the distribution of meteoroid orbits. If on parallel orbits, this *daily drift* of the radiant will be along a small circle parallel to the ecliptic plane.

Finally, it is helpful to realize that the path of Earth through the meteoroid stream is also given by the sum of the velocity vectors (Fig. 4.3). The path makes a shallower angle if the geocentric velocity is larger. The measured duration of a meteor storm (W) is usually larger than the intrinsic width of the trail (W_t).

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[4] E. J. Öpik, Collision probabilities with the planets and the distribution of interplanetary dust. *Proc. R. Irish Acad.* **54** (1951), 165–199.

[5] L. Kresák, Cometary dust trails and meteor storms. *Astron. Astrophys.* **279** (1993), 646–660.

[6] R. Arlt, Radiant ephemeris for the Perseid meteor shower. *WGN* **31** (2003), 19–28.

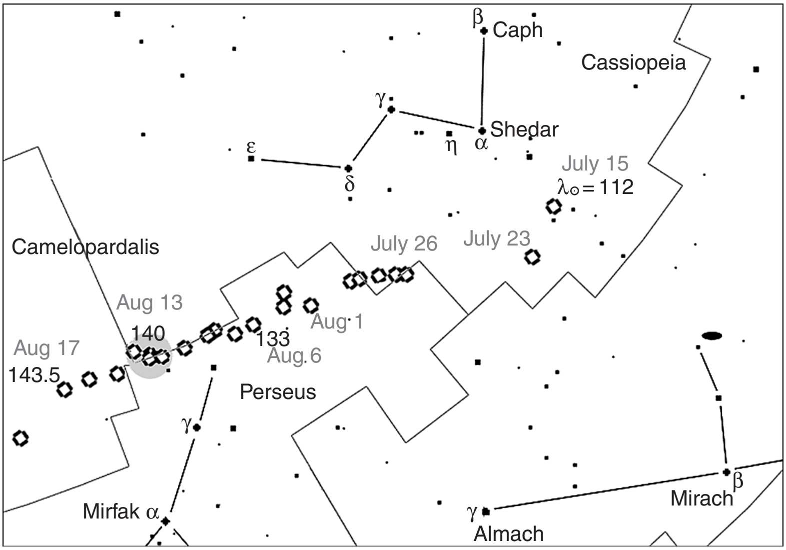

Fig. 4.2 The daily drift of the Perseid radiant from a synopsis of video observations by Rainer Arlt, IMO.

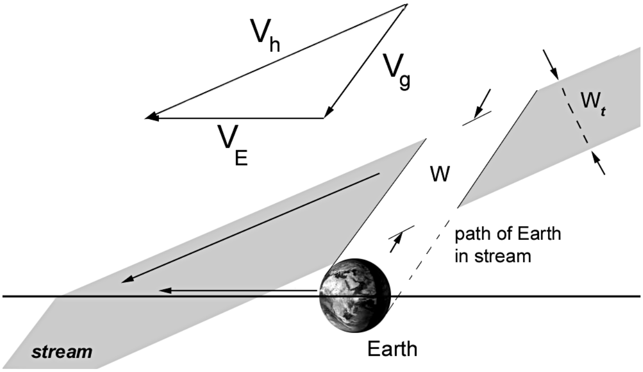

Fig. 4.3 The path of Earth through the meteoroid stream.

4.2 The structure of our atmosphere

After Brandes and Benzenberg, meteors were no longer a meteorological phenomenon. The old atmospheric inflagration explanation of Aristotle still popped up as late as 1892, but by that time it was commonly followed by a swift dismissal (ironically a century later lightning was discovered to reach in the upper atmosphere to the meteor layer in a phenomenon called "sprites." In one instance lightning was observed to travel from the cloud tops to the upper atmosphere, in part, along the ionized trail of a meteor ...[7]).

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[7] E. M. D. Symbalisty, R. A. Roussel-Dupré, D. O. Revelle *et al*., Meteor trails and columniform sprites. *Icarus* **148** (2000), 65–79.

Nevertheless, meteors are observed because the meteoroids collide with the atmosphere. As such, meteors are sensitive probes of the structure of the atmosphere in a range of altitudes that is not easily studied by other means. The first researchers to use this fact were *F. A. Lindemann* and *G. M. B. Dobson* at Oxford University in 1922.[8] At that time, the structure of the atmosphere above 35 km altitude was unknown. They used the height and speed measurements obtained by Denning to show that the air temperature begins to rise again above 50 km and that the density of the upper atmosphere was much higher than previously thought. That temperature rise is on account of warming by ultraviolet (UV) (<200 nm) light from the Sun.

Small variations of meteor rates can occur if the density scale-height at these altitudes alters by a small amount, for example when the atmosphere expands in response to solar activity.[9] Perseid shower rates have been found to be up by 20% in years of low sunspot activity, but the effect has never been established beyond doubt, in my opinion, partially because stream rates may also vary with the orbital period of Jupiter due to planetary perturbations on the same time scale (Chapter 11).[10]

The brightest Leonid fireballs are first seen as high up as 200 km (Fig. 4.4), in a region of our atmosphere called the *thermosphere*.[11] During daytime, this region absorbs the Sun's hard-ultraviolet light, which warms the air (at ground level 78.1% N_2, 20.9% O_2). UV light also breaks molecules and dislodges electrons to create atoms and charged particles, consisting of negatively charged *electrons* and their counterpart, the positive *ions*. This charged, or ionized, part of the atmosphere is called the *ionosphere* (Fig. 4.5).[12]

For a solid particle to slow down significantly, it has to meet more than its own mass in air. Hence, meteoroids penetrate deeper into the atmosphere than the Sun's hard-UV light, down below 120 km and into the cold *mesosphere*. The mesosphere is warmed by the longer wavelength UV sunlight that is absorbed by ozone molecules (protecting us from sunburn). Most ozone molecules are in a layer at about 37 km altitude. Because of this, air temperatures are highest here. Only the largest fireballs penetrate that deep.

The top of the mesosphere, where most meteoroids are stopped, is called the *mesopause*. This is the coldest place on Earth, a frosty $\sim$180 K ($-90\,^\circ$C), with gale winds of 10s of m/s. Fast protons and electrons from the Sun will also sometimes penetrate into the mesopause and cause *aurora* in a circular region around the magnetic poles. For that reason, the mesopause is often considered to be the boundary between the Earth's atmosphere and the Sun's atmosphere. Here on the edge of space, the air density is about 5×10^{-9} g/cm^3 and the pressure about 0.003 mbar. Between 70 and 120 km, the density increases in an exponential manner by a factor of 10 every

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[8] F. A. Lindemann and G. M. B. Dobson, A theory of meteors, and the density and temperature of the outer atmopshere to which it leads. *Proc. R. Soc., London* **102** (1922), 411–437.

[9] C. D. Ellyett and J. A. Kennewell, Radar meteor rates and atmospheric density changes. *Nature* **287** (1980), 521–522; B. A. Lindblad, Meteor radar rates, geomagnetic activity and solar wind sector structure. *Nature* **273** (1978), 732–734.

[10] P. Jenniskens, Meteor stream activity I. The annual streams. *Astron. Astrophys.* **287** (1994), 990–1013.

[11] P. Spurný, H. Betlem, K. Jobse, P. Koten and J. van't Leven, New type of radiation of bright Leonid meteors above 130 km. *Meteoritics Planet. Sci.* **35** (2000), 1109–1115.

[12] M. C. Kelley, *The Earth's Ionosphere. International Geophysics Series*. (New York: Academic Press, 1989).

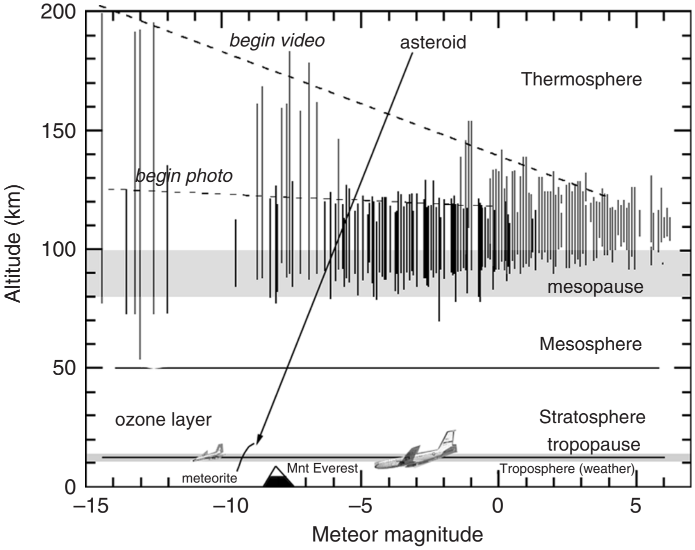

Fig. 4.4 Typical beginning and end heights of Leonid meteors in Earth's atmosphere from recent video and photographic observations by the Dutch Meteor Society.

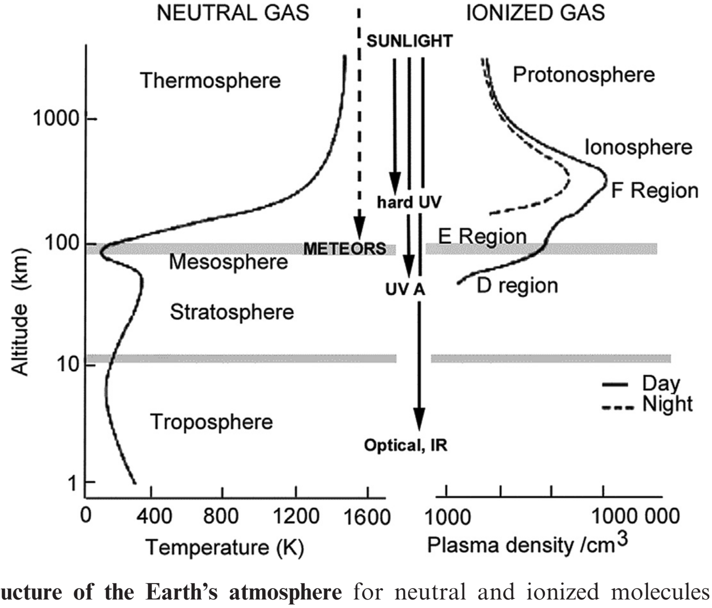

Fig. 4.5 Structure of the Earth's atmosphere for neutral and ionized molecules and atoms (dashed line: night-time). The ionized layers reflect how deep hard-UV light penetrates into the atmosphere.

13 km. Due to this very steep increase in air density, small meteoroids penetrate and deposit most of their mass into a narrow zone at around 89 km altitude. And material deposited higher up will settle down to these denser layers.

The meteors add a sprinkle of metal atoms to the atmosphere, creating a metal atom debris layer. The metal atoms help bring together ozone (O_3) and oxygen (O) atoms created during daytime, and in doing so give off a chemiluminescent glow called *airglow*, which includes the orange glow of sodium atoms. At lower altitudes, the atoms react with atmospheric carbon dioxide (CO_2), and in doing so can attract water molecules and form the core of the tiny ice crystals that make up the *noctilucent clouds* at $\sim$84 km. Ice particles in noctilucent clouds scatter sunlight over the horizon, especially its blue colors, and thus stand out in a bright bluish glow against the dark background of twilight. The ice particles also help sustain ionization and cause sporadic *E layers*, responsible for unusual disturbances in radio and TV reception.

4.3 The mass of a meteor

The high altitudes measured by Brandes and Benzenberg led Professor Olmsted in 1834 to believe that the meteoroids had to be light weight and combustible to explain the high speed and brilliant light.[13] Here we still recognize Aristotle's view on meteors.

However, chemical energy released during burning is not the only potential source of the energy of radiation we call "light." The man who discovered nature's law that the sum of all energy is conserved, *James Prescott Joule* (1818–1889) – his name rhyming with cool, reminded his students to imagine the effect of a cannonball shooting through the classroom.[14] The exploding gun powder causes a cannonball of a mass M to move fast, achieving energy of motion called *kinetic energy*: $E = 0.5\,MV^2$, possibly achieving a speed of $V = 360$ kilometers per hour (km/h). That energy fuels the explosion at the other end of its trajectory. Leonids of the same mass move at 720 times that speed, causing a much bigger explosion, no matter what the makeup.

NASA learned this the hard way when, in January, 2003, a piece of foam hit the reinforced carbon–carbon wing edge of the Space Shuttle Columbia during takeoff. That lightweight piece of foam with a mass of $M = 0.75$ kg (1.7 lb) hit with a velocity of about $V = 850$ km/h (530 mph), or with a kinetic energy of $E = 0.5 \times 0.75\,(850 \times 1000/3600)^2 = 20\,906$ J. In comparison, Leonid meteoroids move at an astounding $V_\infty = 71.6$ km/s (258 000 km/h). Because of that, a fast Leonid meteoroid as light as 0.008 g will pack the same punch as the slower moving large piece of foam! Such a tiny Leonid meteoroid could have caused the same disaster should it have hit the Space Shuttle's wing edge. Because of that impact hazard, no Shuttle flights were executed during the earlier Leonid storms.

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[13] D. Olmsted, Observations of the meteors of November 13, 1833. *Am. J. Sci.* **25** (1834), 354–411.

[14] D. W. Hughes, James Joule and meteors. *Vistas Astron.* **33** (1990), 143–148.

Even if only 1% of that energy is converted into visible light (actual *luminous efficiency* $\tau \sim 0.1-1\%$), then a tiny 0.008 g meteoroid moving at 71.6 km/s would shine like two hundred 100 Watt (= Joule/s) lamps for a whole second. At a distance of 100 km, it would make for a naked eye $+3^{\mathrm{m}}$ Leonid, which solves Olmsted's dilemma.

The mass of a given meteor is usually calculated from a simple scaling equation introduced by Luigi Jacchia and Fred Whipple,[15] valid for the photographic film used in the Harvard Super-Schmidt cameras. This equation follows simply from luminosity being proportional to kinetic energy and an assumption about how the luminous efficiency depends on speed and how "magnitude" is defined. Appendix C gives a corresponding equation for visually observed meteors from a distance of 100 km (m_{v}), strictly for $V_\infty > 25$ km/s and $M < 1$ kg:

$$\log M\ (\mathrm{g}) = 6.31 - 0.40 m_{\mathrm{v}} - 3.92 \log V_\infty\ (\mathrm{km/s}) - 0.41 \log(\sin(h_{\mathrm{r}})) \qquad (4.1)$$

A zero magnitude Leonid of pre-atmospheric speed $V_\infty = \surd(V_{\mathrm{g}}^2 + 11.2^2) = 71.6$ km/s with the radiant at an elevation $h_{\mathrm{r}} = 45°$ would have a mass of $M = 0.13$ g and $\tau = 0.21\%$.

During the 1998 Leonid Multi-Instrument Aircraft Campaign mission, we made an effort to measure the mass of a *Leonid* meteor by probing the neutral iron atom debris left in the path of a meteor, using the University of Illinois at Urbana resonant Fe Boltzmann lidar, in a project led by Chester S. Gardner and Xinzhao Chu (Fig. 4.6), and simultaneously filming the meteors with a high-definition intensified TV camera operated by the Japanese Broadcasting Service (NHK), in a project led by Hajime Yano. The lidar sends pulses of near-UV laser light up to the meteor layer, which are absorbed and re-emitted by the iron atoms in the trail. The time it takes the light pulse to travel up to the meteor layer and back down is used to measure the distance to the trail and its vertical width. The intensity of the scattered light is proportional to the iron atom (Fe) density.

Twenty atom debris trails were detected. In only one case could we identify the meteor that caused the trail: at 17:05:58 UT on November 17, when a $-2.9 \pm 0.3^{\mathrm{m}}$ Leonid passed by the lidar beam just ahead of the direction of flight (Fig. 4.7). A 10 s signal (during which the aircraft moved 1640 m, suggesting a trail FWHM ~1263 m) was detected at 101.14 km altitude peaking at 17:06:59 UT, right when the aircraft was below the train, for which Chu calculated a peak Fe atom density $3.27 \times 10^4\ \mathrm{cm}^{-3}$.[16] One minute after deposition, the trail still had a

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[15] F. Verniani, Meteor masses and luminosity. *Smithsonian Contrib. Astrophys.* **10** (1967), 181–195; L. G. Jacchia, F. Verniani and R. E. Briggs, An analysis of the atmospheric trajectories of 413 precisely reduced photographic meteors. *Smithsonian Contrib. Astrophys.* **10** (1967), 1–139.

[16] X. Chu, W. Pan, G. Papen, *et al.* Characteristics of Fe ablation trails observed during the 1998 Leonid meteor shower. Geophys. Res. Lett. **27** (2000), 1807–1810.

Fig. 4.6 Xinzhao Chu (foreground) and Weilin Pan operate the University of Illinois at Urbana two-beam Fe Boltzmann lidar installed in the NSF/Electra aircraft during the 1998 Leonid MAC mission. Photo courtesy: Chet Gardner, UIU.

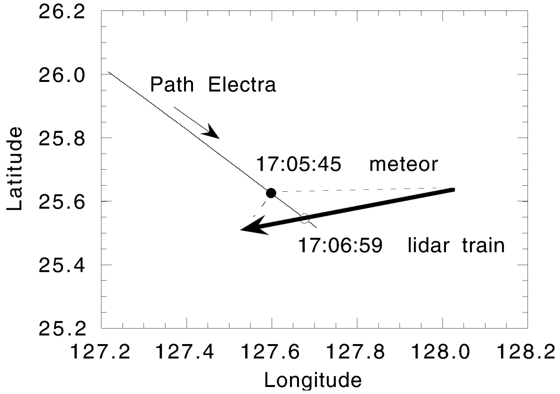

Fig. 4.7 Detection of the neutral atom debris train (open circle) compared to the observed meteor track (line) and moment that the meteor was observed (dot).

vertical rms width of only 63 ± 5 m, but was already ~1640 m dispersed in horizontal direction. From 17:07:15 to 17:07:45 (peaking at 17:07:30 UT), a second detection was made at 100.20 km altitude with only a factor of two lower $Fe = 1.66 \times 10^4\,cm^{-3}$ density, compensated for by the factor of three wider horizontal width. The vertical rms width $= 78 \pm 19$ m. This was probably the same trail, distorted in the upper atmosphere winds.

From the measured Fe density and an expected Fe (55.8 g/mole) abundance fraction by mass of 6.2%, I calculate that the Leonid meteor of -2.9^m at 100 km distance moving at 71.6 km/s deposited 0.25 ± 0.04 g/s matter in atomic form at 101.14 km and 0.48 ± 0.07 g/s at 100.20 km. That mass represents a kinetic energy deposition of 0.64 and 1.2×10^6 J/s, respectively. The visible light output of the meteor is 13 800 W, so that $\tau = 2.2 \pm 0.4\%$ and $1.2 \pm 0.2\%$, respectively.

According to Eq. (4.1), 0.21% of kinetic energy is transferred into light. If this estimate is correct, then much mass is not counted. The lidar does not detect the iron atoms that are in ionized or solid form. At ambient temperatures, all iron atoms should be in neutral form, albeit that the recombination process takes some time and starts from a high $Fe^+/Fe \sim 3600$ in the meteor plasma itself. If most of the ions had recombined by the time of the lidar measurement, as expected, then I conclude that as much as 90% of a Leonid meteoroid ended up as solid debris instead of atoms! This may explain why other researchers have found that neutral atom debris trains can vary strongly in the relative composition of the expected meteoric metal atoms.[17]

The meteor light is a combination of emission lines from metal atoms from the meteoroid itself and broad emission bands from the collisionally excited atmospheric molecule N_2 (Fig. 4.8). By putting a so-called *transmission grating* in front of the lens of a camera, astronomers disperse the light into all colors of the rainbow and can thus distinguish the contribution of each atom or molecule. Each color of light creates a separate image of the point-like meteor. The result is called a spectrum (Fig. 4.8). Under normal conditions, that spectrum is surprisingly independent of meteor mass and speed,[18] although the relative contributions of air plasma and metal atoms vary a lot. Note that equation (4.1) does not take into account such changes in the ratio of air plasma and metal atom emissions that are responsible for most observed color changes in meteors.

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[17] U. Von Zahn, M. Gerding, J. Höffner, W. J. McNeil and E. Murad, Iron, calcium, and potassium atom densities in the trails of Leonids and other meteors: strong evidence for differential ablation. *Meteoritics Planet Sci.* **34** (1999), 1017–1027.

[18] P. Jenniskens, C. O. Laux, M. A. Wilson and E. L. Schaller, The mass and speed dependence of meteor air plasma temperatures. *Astrobiology* **4** (2004), 81–94.

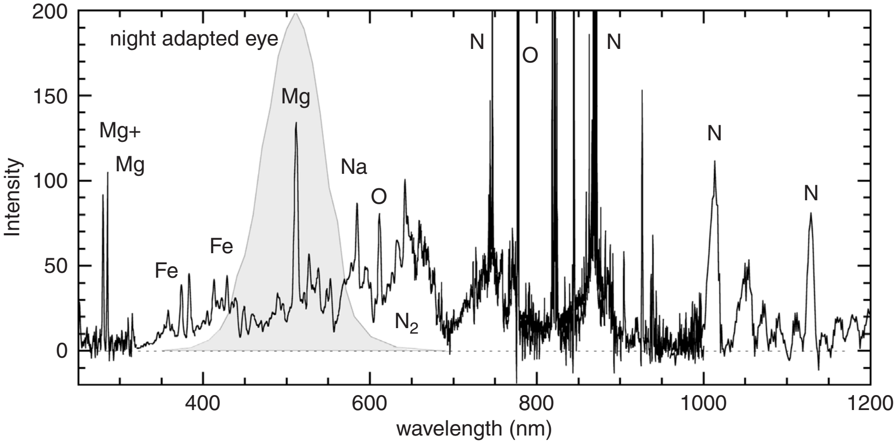

Fig. 4.8 Spectrum of a typical -2^m Leonid meteor from ultraviolet (left), over violet, blue, green, yellow, and red, into the near-infrared. Compilation of observations from the *Leonid MAC* campaign in different wavelength regimes (and at different spectral resolutions).

4.4 How meteors emit light

The particulars of how a meteor emits light and what compounds and debris are deposited in Earth's atmosphere are not important to understand the rest of this book and the uninterested reader may want to skip to Chapter 5. These details do matter, however, when meteor showers are used to study the delivery of organic compounds at the time of the origin of life, the supply of metal atoms to the upper atmosphere, or how efficiently the meteoroids of different streams are detected by high-aperture radar, just to mention a few good reasons to read on.

What matters is not just how much energy is available, but how that energy is used. If the energy is only used to break the atomic bonds of the meteoroid, then there is enough kinetic energy to break every single bond in a Leonid meteoroid some 50 times. Indeed, with all those metal atom lines shining bright, it seemed obvious that the whole of the meteoroid was atomized.

In reality, much can remain in solid or molecular form. Most energy goes into heating the air and the process of evaporation can carry away much of the heat imposed on the meteoroid. Because of that, for example, some of the rocky matter of asteroids survives the impact if the impact speed is less than about 22 km/s. The recovered pieces are called *meteorites*. Meteorites have only a thin crust of molten rock and stay at their original hand-warm temperature inside. That crust is a black opaque glass, made dark by sub-micrometer-sized inclusions of magnetite (Fe_3O_4). In this case, the heat is lost by rapid evaporation.

In the same manner, small grains can lose heat efficiently by radiation, if the meteoroids are larger than the wavelength of infrared light. At sizes smaller than the wavelength of infrared light, that radiation process is not efficient. Because of this, tiny 5–50 μm dust grains arriving at a slow ~11 km/s can survive the impact nearly intact, creating *micro-meteorites*, but even smaller grains do not survive.

The classical 1958 book by Ernst Julius Öpik: *Physics of Meteor Flight in the Atmosphere*,[19] and the more recent 1983 book by Vitalij Aleksandrovich Bronshten, *Physics of Meteoric Phenomena*,[20] describe the basic processes of meteor entry in terms of how hot a meteoroid can become and how much matter is lost. I will not repeat this. The reader is referred to these excellent books and that of McKinley.[21]

The recent Leonid storm observing campaigns provided more insight into the actual physical conditions and the fate of the meteoric matter. We now know that at high altitudes (up to 250 km) *sputtering and the subsequent collision cascade* of metal atoms and air molecules with the ambient environment is the dominant luminous mechanism. Colliding air molecules cause meteoric metal atoms to be ejected at speeds in excess of the entry velocity of the meteoroid. The subsequent cascading collisions with the atmosphere result in a broad V-shaped glow, which becomes narrower the deeper the meteoroid penetrates into denser air layers.[22] Sputtering does not significantly depend on the surface temperature of the grain.

Below about 136 km, rapid evaporation adds to the sputtering, the latter accounting for no more than 10% of the total ablation for a 0.01 g grain. The meteoroid surface starts to warm up to the point where minerals near the surface of the grains melt and evaporate in the form of atoms and molecules. An *ablation vapor cloud* is formed that travels along with the meteoroid and surrounds the meteoroid out to a size comparable to the distance an ambient air molecule can travel before hitting another molecule (Fig. 4.9). This *mean free path* is of the order of 1 m at 111 km, 10 cm at 96 km, 1 cm at 83 km, and 1 mm at 68 km altitude. Each impact with an air molecule will evaporate up to 80 atoms and molecules from the surface of the meteoroid. The most important effect of the vapor cloud is to greatly expand the surface area now exposed to collisions, increasing the rate of collisions and hence the brightness of the meteor. The lightcurve of the meteor will show a rapid increase at the onset of this rapid evaporation.

It is only when the meteoroid is larger than this mean-free path, that the molecules start colliding with each other in front of the meteoroid and a shock wave is formed. It is said that the airflow changes from *rarified* to *continuum flow*. Very rarely, this shock wave penetrates deep enough in the atmosphere that it can be heard as a distant rumble long after the fireball is seen. In such exceptional cases, the sound traveling at about 270–350 m/s takes several minutes more to reach us than the nearly instantaneous visible light. Meteors do not normally cause audible sounds. Hence, they will pass by unnoticed if not seen. But hissing sounds ("crackling," "rushing,"

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[19] E. Öpik, *Physics of Meteor Flight in the Atmosphere* (New York: Interscience, 1958); B. Yu. Levin, *Physikalische Theorie der Meteore und die meteoritische Substanz im Sonnensystem*, vol. II. *Scientia Astronomica* 4. (Berlin: Akademie-Verlag, 1961), 330 pp.

[20] V. A. Bronshten, *Physics of Meteoric Phenomena*. (Dordrecht: Reidel, 1983), 356 pp.

[21] D. W. R. McKinley, *Meteor Science and Engineering* (New York: McGraw-Hill, 1961), Chapter 7.

[22] Presentations by: D. Vinkovic, O. Popova, R. L. Hawkes *et al. Meteoroids 2004 Conf.*, London, Ontario, Canada.

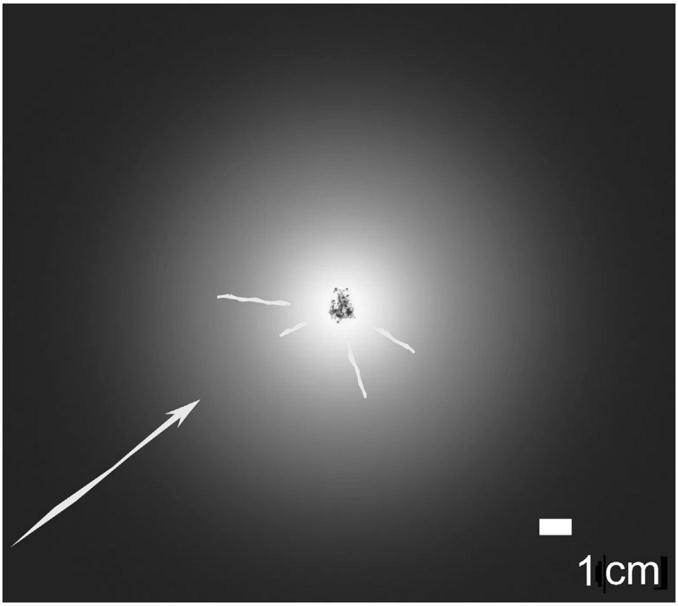

Fig. 4.9 The creation of an ablation vapor cloud upon bombardment of a meteoroid by air molecules.

"popping," "vits," and "sharp clicks") have been reported for very bright meteors. Although still a contentious issue, these sounds are thought to be due to very low frequency (VLF) radio waves interacting with metal, paper, or other electrically conducting materials in the environment.[23]

When air molecules hit the meteoroid or vapor cloud, they speed up relative to the ambient air, but not as fast as the meteoroid, and immediately lag behind. At the same time, the vapor cloud atom is slowed down relative to the meteoroid, lagging behind as well. Both will continue to bounce off many ambient air molecules before slowing down (Fig. 4.10). This cascade of collisions with ambient molecules is called the *cascade phase*, and is responsible for impact excitation of a "hot" component in meteor spectra, dominated in the visual region by light from ions of the elements magnesium, calcium, and silicon. This hot component is most clearly seen in high-velocity or bright meteors.

When the molecules and atoms finally slow down, a column of warm *air plasma* is created with an initial radius of the order of a few meters, mainly determined by the mean free path. This column quickly expands to tens of meters diameter (*expansion phase*) to establish pressure equilibrium with the surroundings (Fig. 4.11). At higher elevations, the original mean-free path and the subsequent dilution is large and the

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[23] C. S. L. Keay, Anomalous sounds from the entry of meteor fireballs. *Science* **210** (1980), 11–15; M. Beech and L. Foschini, Leonid electrophonic bursters. *Astron. Astrophys.* **367** (2001), 1056–1060.

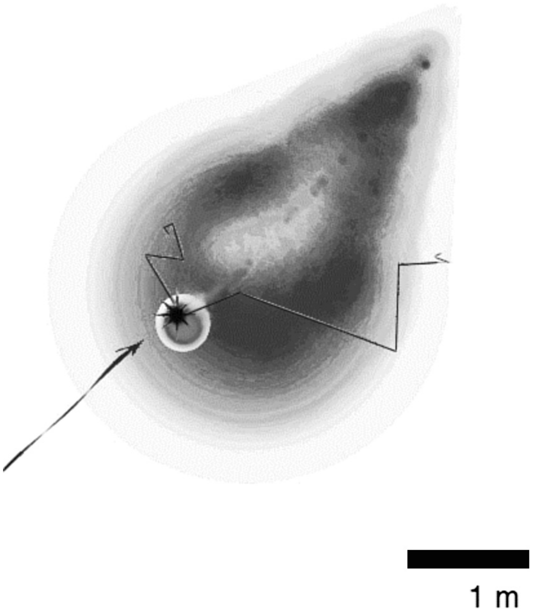

Fig. 4.10 The cascade of collisions in the region behind the meteoroid in the cascade phase.

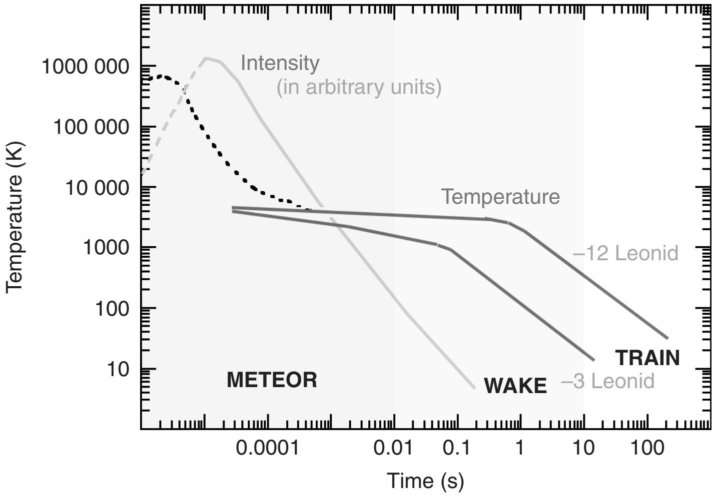

Fig. 4.11 Temperature and intensity in the path of the meteoroid since the meteoroid passed by. Measured temperatures are relative to the ambient atmospheric temperature. The intensity of the meteor is in arbitrary units. A summary of results from the Leonid MAC observations. The dashed lines are results from theoretical models.

electrons generated in the impacts diffuse more rapidly.[24] There is a height above which no radar meteor echoes are detected, which is known as the *echo height ceiling* in back-scatter radar.

The light of meteors originates mostly from this warm *air plasma* due to processes similar to those in discharge lamps such as the familiar low pressure yellow–orange sodium lamps. The plasma is warm, at about 4400 K, and energetic collisions are common. In collisions, electrons bound to those metal atoms such as sodium are knocked into distinct excited states with orbits at larger mean distances from the nucleus of the atoms. When the electrons fall back to their rest positions, light is emitted at very specific wavelengths (orange in the case of sodium, blue–green for magnesium). Light is also emitted from the air molecules that take part in those collisions. Rather than specific emission lines, molecules create bands of light spread over a range of wavelengths that are a reflection of all the vibrational and the rotational states induced by the collisions (Fig. 4.8). The total intensity of light (and the electron density: this is also the region from which the moving radar signals bounce that are called *meteor head echoes*) is proportional to the amount of kinetic energy (meteor mass) deposited in the air at any given moment.

During the 2001 Leonid Multi-Instrument Aircraft Campaign, Hans Stenbaek-Nielsen of the University of Alaska at Fairbanks discovered that Leonids brighter than -3^{m} show a halo around the meteoroid, with a bite-out that is shaped like a shock wave (Fig. 4.12). This halo is now interpreted as the result of hard ultraviolet light generated in collisions in the vapor cloud. This light is absorbed by trace molecules in the air and re-radiated as visible glow.[25]

The size of that glow reflects the decreasing intensity of the UV light source away from the meteoroid. This is an astounding several hundreds of meters around a 1 cm meteoroid (the air pressure is only one millionth of that at the surface). In those same meteors, a shock-like feature has been observed, the source of which is possibly a shadow from the vapor cloud.

The classical lightcurve of a meteor (dashed lines Fig. 4.13) is one in which the meteor brightens exponentially due to the rapidly increasing air density deeper down in the atmosphere, then peaks and fades when the meteoroid becomes smaller.[26]

In practice, there is usually fragmentation of the meteoroid early in its trajectory, after which the meteoroid consists of a number of individual fragments. These

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[24] From the decay of radar echoes at wavelength λ with time constant t_{d}, the electron diffusion coefficient, defined as $t_{\mathrm{d}} = \lambda^2/(16\pi^2 D)$, was measured to increase exponentially from $D = 1\,\mathrm{m^2/s}$ at 84 km to $D = 400\,\mathrm{m^2/s}$ at 120 km altitude. The classical rate of diffusion of the trail radius is $r = r_0(1 + 4Dt^2)$, with initial radius $r_0\,\rho_\alpha^{-0.25} V^{0.6}$ is 63 cm at 20 km/s increasing to 123 cm at 60 km/s at 100 km altitude, 22 cm at 20 km/s increasing to 42 cm at 60 m/s at 75 km altitude. W. G. Elford, Radar observations of meteors. In *Meteoroids and Their Parent Bodies, Proc. IAS Symp. Meteoroids and Their Parent Bodies*, ed. J. Stohl and I. P. Williams (Bratislava: Inst. Slovak Acad. Sci., 1992), pp. 235–244.

[25] H.-C. Nielsen and P. Jenniskens, A “shocking” Leonid meteor at 1000 fps. *Adv. Space Res.* **33** (2004), 1459–1465; P. Jenniskens and H.-C. Stenbaek-Nielsen, Meteor wake in high frame-rate images – implications for the chemistry of ablated organic compounds. *Astrobiology* **4** (2004), 95–108.

[26] The classical light curve can be expressed in terms of air density (ρ_{a}) (from McKinley 1961):

$$I/I_{\max} = \frac{9}{4}\rho_{\mathrm{a}}/\rho_{\mathrm{a}}^{\max} \times (1 - \rho_{\mathrm{a}}/3\rho_{\mathrm{a}}^{\max})^2 \tag{4.2}$$

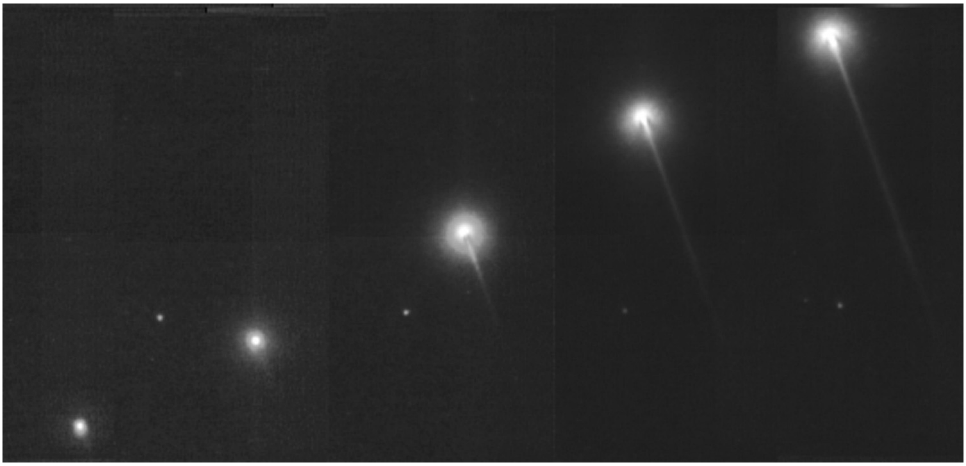

Fig. 4.12 A -3^m Leonid meteor in 1 ms snapshots by Hans Stenbaek-Nielsen of the University of Alaska at Fairbanks. This meteor developed a shock-like feature in a halo of light.

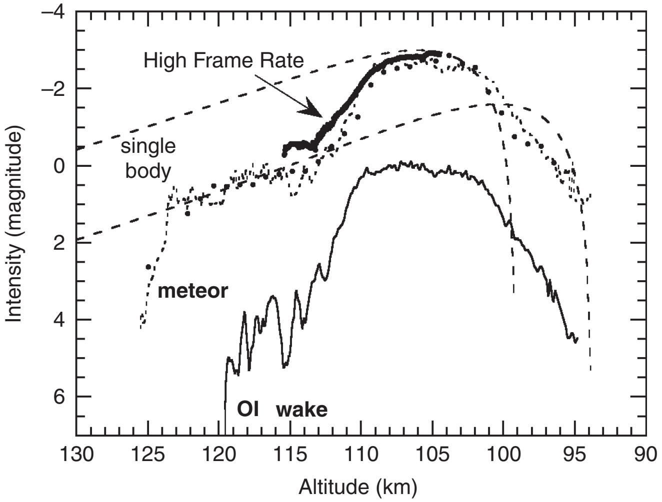

Fig. 4.13 The lightcurve of the Leonid meteor of Fig. 4.12 and that of its OI wake. The dashed lines show the expected lightcurve for a single body.

fragments come down together because the low air density is not efficient at stopping them. This is called the *dust-ball* model of meteor light curves. Deeper into the atmosphere, the smallest fragments are slowed down most and form a wake of debris particles, with the larger fragments penetrating most deeply. If a single fragmentation event creates a spray of tiny particles, each weighing no more than 1 millionth of a gram, a brief *flare* may be observed.[27] Meteor flares show a very abrupt onset. The

[27] H. J. Smith, The physical theory of meteors. V. The masses of meteor-flare fragments. *Astron. J.* **119** (1954), 438–442.

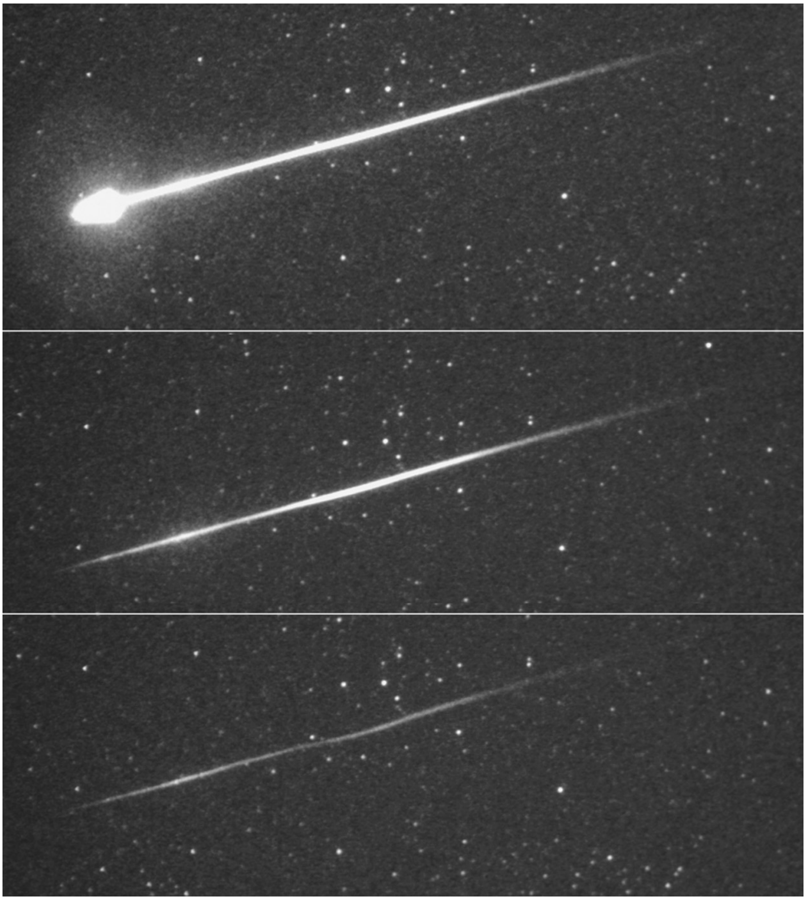

Fig. 4.14 Forbidden green line luminescence in the wake of the 02:15:39 UT (Nov. 18, 1999) Leonid, filmed by an NHK Hivision HDTV-II camera onboard the 1999 Leonid MAC mission. Photo courtesy NHK and Hajime Yano, ISAS.

increased ablation rate will cause an increase of metal atom line emission, often causing the meteor to turn green. Moreover, the large ablation vapor cloud will cause more cascade-phase radiation from the "hot component."

The warm air plasma stretches 5–50 m behind the meteoroid, then fades when it cools and collisions become less frequent. The cooling is gradual enough (and inhibited by continued secondary ablation from debris) to sometimes cause a brief *afterglow* in the meteor images, usually lasting less than a second or two.

Sometimes there is also a slightly longer lasting *wake* due to emission generated by free electrons that find their way back to ions, called *recombination line emission*.[28]

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[28] J. Borovicka and P. Koten, Three phases in the evolution of Leonid meteor trains. *ISAS SP* **15** (2003), 165–173.

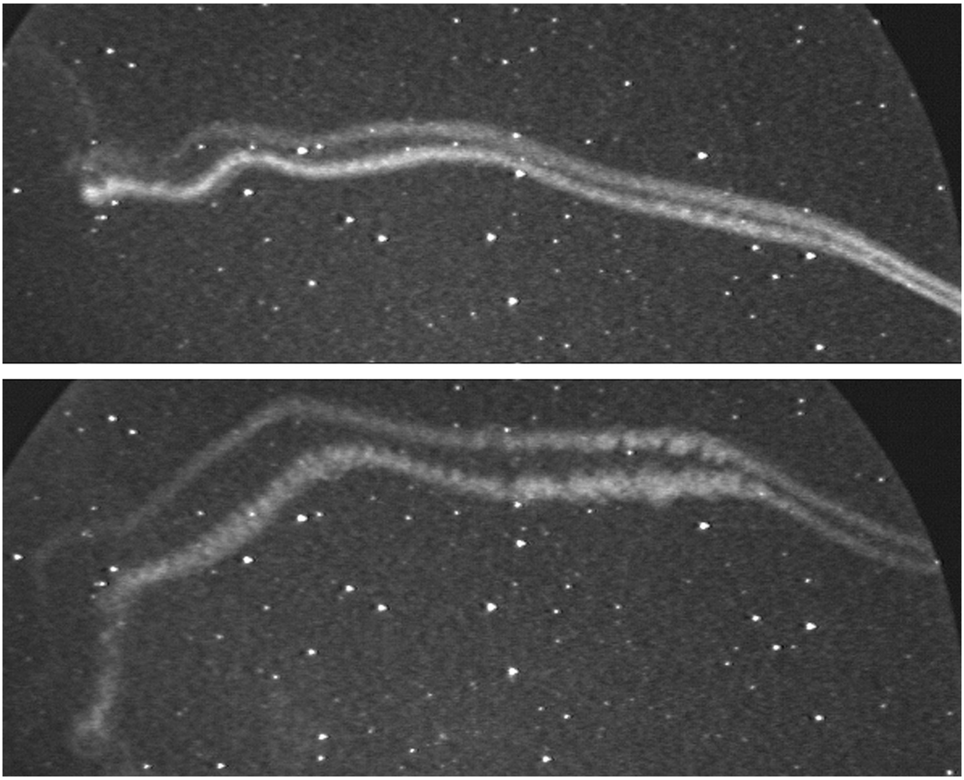

Fig. 4.15 Persistent train 40 and 72 s after a Leonid fireball passed by from right to left. This train lasted 9 min. Photo by Kouji Maeda (Miyazaki Astronomical Group).

This emission can last up to several tens of seconds. The ionization efficiency per gram varies with entry speed $\sim V^5$, making this a more dominant phenomenon in fast Leonid meteors.[29] This emission is very different from that of the meteor itself or its afterglow, containing high energy transitions that do not occur as a result of thermal collisions.

Visual observers can see that fast meteors have a 1–10 s *wake* caused by the “forbidden” 557 nm green line luminescence of oxygen atoms (Fig. 4.14). Forbidden, because the final relaxation step in the energy diagram of oxygen atoms is not allowed by quantum mechanical rules.

Bright fragile meteoroids continue to leave a *persistent train*. Only during the recent Leonid MAC missions was it discovered what is responsible for the eerie glow. Its light derives from chemiluminescence of iron oxide (FeO) molecules and sodium atoms

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[29] F. L. Whipple, The physical theory of meteors. VII. On meteor luminosity and ionization. *Astrophys. J.* **121** (1955), 241–249.

(Na), because meteoric iron and sodium atoms participate as catalysts in the recombination reactions of oxygen atoms and ambient ozone molecules.[30]

The glow can persist for many minutes at 95–75 km altitude and thus trace the prevailing winds at those altitudes. Variations in air pressure and density called *gravity waves* are caused by hot air bubbles that buoyantly rise from the troposphere and expand with increasing altitude. These bubbles have wind directions that change rapidly with altitude, causing the familiar corkscrew patterns in windblown trains.

Many persistent trains show two parallel lanes of billows, whereby the amount of billowing can vary (Fig. 4.15). John Zinn (LANL) at the 2003 Leonid MAC workshop explained that the cylinder of low density hot-air in the path of the meteoroid displaces the overlaying column of air more so at the center of the cylinder. Hence, the center will rise more rapidly by buoyancy than the edges, which results in a breakup of the hot air column into two oppositely rotating cylindrical line vortices.[31]

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[30] P. Jenniskens, M. Lacey, B. J. Allan, D. E. Self and J. M. C. Plane, FeO “Orange Arc” emission detected in optical spectrum of Leonid persistent train. *Earth, Moon Planets* **82–83** (2000), 429–438.

[31] J. Zinn and J. D. Drummond, Observations of persistent Leonid meteor trails: 4. Buoyant rise/vortex formation as mechanism for creation of parallel meteor train pairs. *J. Geophys. Res. Lett.* **110** (2005), A04306.

5

Comet and meteoroid orbits

The forecasting of meteor storms is all about knowing the orbit of the meteoroids and their parent body in the past, present, and future. When I first learned about meteor orbits in space, I found it very hard to imagine the orbit in three dimensions. Modern computer games and 3D software tools have made it easier to visualize a comet orbit in space, but there remains a need to express the shape and orientation of an orbit with numbers, the so-called *orbital elements*. The astronomical language of orbital elements is the $qae\omega\Omega i$-system[1].

5.1 Orbital elements

Theoretical astronomers still like to give position and motion by three positional coordinates X, Y, Z, which give the location of a comet or meteoroid at a given time, and three velocity coordinates V_x, V_y, V_z, which describe the direction of its motion. They tell us, for example, that the comet on January 1, 2005, is at $-1.223\,15$, $+0.352\,52$, $+0.025\,33$ AU (1 AU = the Earth–Sun distance) and moves at a speed of $+22.5251$ km/s towards the X-direction, at $+12.1523$ km/s towards Y, and at $+2.1523$ km/s towards Z. However, from that it is hard to imagine what type of orbit the comet is in, or how it will move in the future.

Everyone else uses the fact that comets and their offspring move in elliptical orbits around the Sun. The orbits are more elongated than those of the planets and tilted out of the plane of Earth's orbit called the "*ecliptic plane*". The orbital elements describe the shape and orientation of the ellipse (Fig. 5.1) by a system of six numbers (and a variety of derivatives): the size and shape of the orbit (two numbers: q and a), the orientation of the orbital plane (three numbers: ω, Ω, i), and the position in the orbit (one number: T_p).

The shape and size of the ellipse – is described by two numbers: the distance from the Sun (strictly the focal point of the ellipse) at closest approach, called *perihelion distance*, usually assigned the letter "q," and the size of the ellipse, expressed in terms of the *semimajor axis* (letter "a"), with $2 \times a$ being the length of the longest axis of

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[1] C. D. Murray, S. F. Dermott, *Solar System Dynamics*. Cambridge University Press, Cambridge (1999), 592 pp.

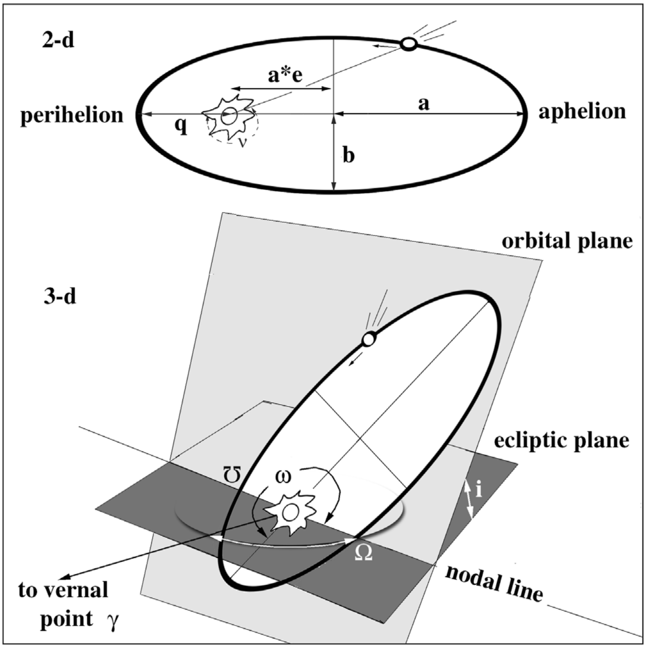

Fig. 5.1 A definition of the orbital elements of a comet or meteoroid orbit in the solar system in two and three dimensions. The line from perihelion to aphelion is called the line of apsides.

the ellipse. Derivative numbers include the point furthest from the Sun, which is called the *aphelion distance*, assigned the letter "Q". The distance between q and Q is twice the semimajor axis. Another derivative is the time it takes to complete one revolution, which is called the *orbital period* (symbol $P = \sqrt{a^3}$). The shape of the ellipse can also be defined by the *eccentricity* (letter e), defined as ae is the distance from the Sun to the midpoint of the ellipse. The eccentricity is usually derived from the equations:

$$q = a(1 - e) \quad \text{or} \quad Q = a(1 + e) \tag{5.1}$$

The eccentricity is $e < 1.0$ for an elliptic orbit, $e = 1.0$ (and $1/a = 0$) for a parabolic orbit, and $e > 1.0$ ($1/a < 0$) for a hyperbolic orbit.

The orientation of the ellipse in space – relative to the ecliptic plane – is defined by three angles. The angle between comet orbital plane and the ecliptic is called the *inclination* of the orbit (i), measured between 0° and 180° (360° being a full circle). The *nodal line* is the intersection of these two planes and its orientation is called the *longitude of the ascending node* (Ω), or *node* for short. The angle is measured between 0° and 360°, and measured from the direction of the spring point (= *vernal equinox*) in the constellation of Pisces. A derivative is the descending node ($℧ = \Omega + 180°$). Finally, the orientation of the ellipse (anchored at the focal point where the Sun is), or direction of perihelion in the plane of the comet orbit, is expressed with the *argument of perihelion* (ω), measured from the direction of the ascending node. The derivative parameter "*longitude of perihelion*" $\Pi = \omega + \Omega$ gives the direction of perihelion measured from the vernal point. The pronunciation of Greek letters is given at the end of this book.

The positions of the comet and the meteoroid in their orbits can be expressed as the moment in time when the comet passes by perihelion, the *perihelion time* (T_p), or alternatively as an angle (*anomaly*) measured from perihelion in the direction of motion along the orbit.[2] A derivative number used for meteor showers is the moment when passing by Earth (the node of the orbit). The *eccentric anomaly* is the angle measured around the center of the ellipse, the *true anomaly* (v) is the angle measured with the Sun at the center.

The motion along the ellipse is not constant. In an eternal swapping of kinetic and potential energy, a comet speeds up while falling in the gravity well of the Sun, then loses that speed again when moving back out. The effect is similar to the roller coaster ride that comes to a near stop at the top of the hill before rushing down again. As a result, comets and meteoroids spend much of their time close to aphelion (the top of the hill).

The *Vernal*, or *Spring equinox* is the direction where the equatorial plane intersects the ecliptic plane. Because the Earth's spin axis changes direction in space continuously like the axis of a tilted spinning top, the orientation of the equator changes and the vernal equinox moves with about $+0.013\,96^\circ$/yr towards Capricorn. Because of this spin axis *precession*, all orbital element angles need to be expressed in a coordinate system that is valid for a given position of the *equinox*, such as on January 1 11:58:55.816 UTC UT in the year AD 2000 (J2000). And because the orbital elements change with time even over one orbit due to the gravitational pull of the planets, they are really valid only for a given *epoch*, or moment in time. Instantaneous orbital elements, describing the unperturbed elliptical orbit based on speed and position at any given moment, are called *oscular orbital elements*, from the Latin verb *osculare*, meaning "to kiss". Throughout this book, I will use J2000 and the epoch being the time of perihelion passage of the comet or the moment the meteoroid is observed, unless otherwise specified.[3]

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[2] *The position of the comet or meteoroid* – in the ellipse can be expressed in terms of the time since perihelion passage (T), when the *mean anomaly* $\mathcal{M}$ is defined as: $\mathcal{M} = 360^\circ\,(t - T)/P$. The comet will speed up near perihelion and slow down at aphelion. The *true anomaly*, the angle $v =$ perihelion – Sun – comet, gives the actual angular position of the planet in its orbit. Calculating v, is an iterative process. First, calculate the *eccentric anomaly* $E =$ the angle perihelion – midpoint ellipse – comet: $E = \mathcal{M} + e\ \sin(\mathcal{M})\ (1 + e\ \cos(\mathcal{M}))$. Then iterate using $E' = E$, $E = E' - (E' - e\ \sin(E') - \mathcal{M})/(1 - e\ \cos(E'))$, until the magnitude of $E - E'$ is sufficiently close to zero. Finally, the true anomaly v relates to E as: $v = 2\tan^{-1}\{\surd[(1 + e)/(1 - e)]\ \tan(E/2)\}$.

It is useful to realize that when a meteoroid is observed at Earth, it is in either the ascending or the descending node. If it is in the ascending node, then $v = 360 - \omega$ (Fig. 5.1). If it is in the descending node, then $v = 180 - \omega$.

[3] Here, the "J" stands for "Julian," meaning that the year is defined as having precisely 365.25 d. In the old form of "B1950.0", for example, the "B" meant "Besselian," with the year being the tropical year of 365.2421988 d. This affects the definition of the date of the epoch and therefore the exact position of the meteoroid or comet at a given time, but only by a very small amount. The coordinate system adopted by the *International Astronomical Union* is that of the *International Celestial Reference System*, with its origin in the Solar System barycenter, and in which use of the "mean" equator and equinox of J2000 means that nutation of the Earth's spin axis is averaged out or omitted altogether.

5.2 Miss distance

For a meteoroid to hit Earth, the heliocentric distance of the nodes has to be close to the heliocentric distance of Earth. The heliocentric distance at any point along the orbit, for a given position with *true anomaly* (v) is given by:[4]

$$r = q(1 + e)/[1 + e\cos(v)] \tag{5.2}$$

Substituting $v = \omega$, for the ascending node, or $\omega + 180°$ for the descending node, gives the heliocentric distance (r) of that node, respectively.[5]

Compare this to the heliocentric distance of Earth (r_E) at the point of intercept which follows from Eq. 5.2 with $q = 0.983\,289\,90$ AU, $e = 0.016\,710\,22$, and $v = \Omega - 91.686\,55°$ for the ascending node or $v = \Omega + 88.313\,4537°$ for the descending node. The *nodal miss-distance* is defined as: $\Delta r = r - r_E$. This is not always the shortest distance between the Earth's orbit and the comet orbit (δ in Fig. 5.2), especially for low-inclination orbits. This difference plays a role in calculating the maximum time of a shower and to some extent the theoretical radiant, if the orbit does not intersect that of the Earth. For low inclination showers with a node far from Earth's orbit, the difference can be quite large ($\Delta\Omega$).

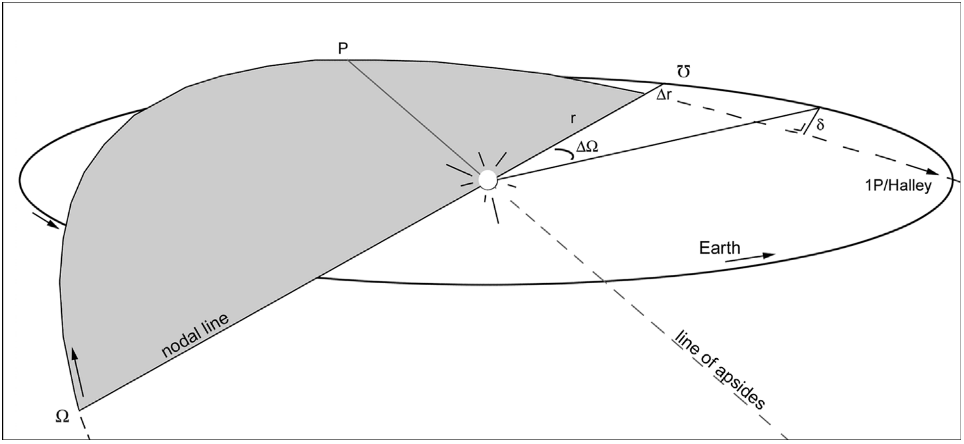

Fig. 5.2 Illustration of the difference between the nodal miss-distance (Δr) and the shortest distance (δ) between comet Halley's orbit and Earth's orbit.

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[4] *The position of the comet or meteoroid* – in the ellipse can be expressed in terms of the time since perihelion passage (T), when the *mean anomaly* $\mathcal{M}$ is defined as: $\mathcal{M} = 360° (t - T)/P$. The comet will speed up near perihelion and slow down at aphelion. The *true anomaly*, the angle v = perihelion – Sun – comet, gives the actual angular position of the planet in its orbit. Calculating v, is an iterative process. First, calculate the *eccentric anomaly* E = the angle perihelion – midpoint ellipse – comet: $E = \mathcal{M} + e \sin(\mathcal{M})\ (1 + e \cos(\mathcal{M}))$. Then iterate using $E' = E$, $E = E' - (E' - e \sin(E') - \mathcal{M})/(1 - e \cos(E'))$, until the magnitude of $E - E'$ is sufficiently close to zero. Finally, the true anomaly v relates to E as: $v = 2 \tan^{-1} \{\sqrt{[(1 + e)/(1 - e)]} \tan(E/2)\}$.

It is useful to realize that when a meteoroid is observed at Earth, it is in either the ascending or the descending node. If it is in the ascending node, then $v = 360 - \omega$ (Fig. 5.1). If it is in the descending node, then $v = 180 - \omega$.

[5] G. S. Hawkins, R. B. Southworth and F. Steinon, Recovery of the Andromedids. *Astron. J.* **64** (1959), 183–188.

There are different ways to adjust the comet orbit so that it intersects with Earth. Long-time director of the B.A.A., *John Guy Porter*,[6] first described a method, used later by Jack Drummond and Duncan Olson-Steel, where the direction of the comet orbit at the node is simply rectilinearly transposed to the orbit of Earth. This is not how a meteoroid orbit differs from a comet orbit. *Ishiro Hasegawa*[7] proposed a technique whereby the line of apsides of the comet orbit is rotated until the orbit intersects Earth's. This assumes a particular mechanism of evolution (precession, see later), which does not apply to young showers, and assumes that the shape of the orbit does not change, which is not the case for old showers. Another way is to change q and ω in unison, but keep Π constant, or to change the semimajor axis a. For low-inclination streams, the results can differ significantly. The only good method would be to calculate a theoretical radiant from the history of the meteoroid orbit since ejection until it can hit Earth. That is a lot of work, but there are relationships between orbital elements that can sometimes be used to get a good guess of how the orbit changes over time.[8] These methods were summarized in a software program by *Lubos Neslusan* of the Astronomical Institute of the Slovak Academy of Sciences,[9] which was used here to calculate theoretical radiants.

5.3 Reservoir of Jupiter-family comets: the Kuiper Belt

With this system of orbital elements, it is possible to study the origin and evolution of comet orbits. Comets originate in large reservoirs in the outer regions of our solar system. Many short-period comets ($P < 20$ yr) tend to move in the same direction (prograde) as the planets. Because they do not survive long in the inner solar system, there has to be a continuous supply. *Gerard Peter Kuiper*[10] (1905–1973), and before him *Kenneth Essex Edgeworth*[11] (1880–1972), proposed that a remnant of planetesimals just outside of Neptune's orbit could be the reservoir. This *Kuiper Belt* (sometimes called the *Edgeworth–Kuiper Belt*) are planetesimals that never grew into a larger planet.

The first comet still in the Kuiper Belt, was found in 1992 by *David Jewitt* and *Jane Luu* (1992 QB_1, nicknamed "Quebewan"), now called a *Kuiper Belt object* (KBO). These are also called *Trans-Neptunian Objects*, which are all objects that permanently reside outside of Neptune's orbit. Most found so far are between 30 and 50 AU from

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[6] J. G. Porter, *Comets and Meteor Streams* (London: Chapman and Hall, 1952).

[7] I. Hasegawa, Y. Ueyama and K. Ohtsuka, Predictions of the meteor radiant point associated with an Earth-approaching minor planet. *Publ. Astron. Soc. Japan* **44** (1992), 45–54.

[8] P. B. Babadzhanov, Formation of twin meteor showers. In *Asteroids, Comets, Meteors III*, ed. C.-I. Lagerkvist, *et al.* (Uppsala: University of Uppsala, 1990), pp. 497–503.

[9] L. Neslusan, J. Svoren and V. Porubčan, A computer program for calculation of a theoretical meteor-stream radiant. *Astron. Astrophys.* **331** (1998), 411–413.

[10] G. P. Kuiper, On the origin of the solar system. In *Proc. Topical Symposium, Commemorating the 50th Anniversary of the Yerkes Observatory and Half a Century of Progress in Astrophysics*, ed. J. A. Hynek. (New York: McGraw-Hill, 1951), p. 357.

[11] K. E. Edgeworth, The evolution of our planetary system. *J. Br. Astron. Assoc.* **53** (1943), 181–188; K. E. Edgeworth, The origin and evolution of the solar system. *Mon. Not. R. Astron. Soc.* **109** (1949), 600–609.

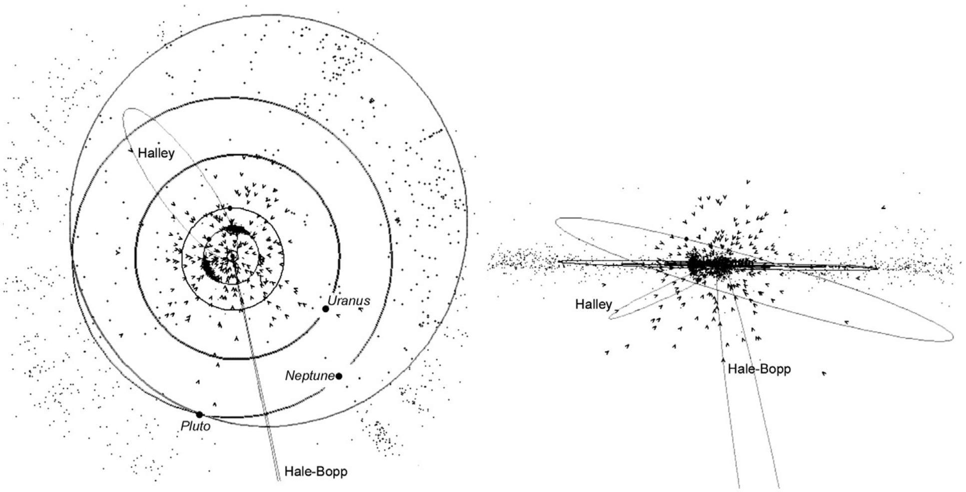

Fig. 5.3 Kuiper Belt: position of all known comets in the inner solar system (V) and in the Kuiper Belt (●) with a semimajor axis larger than 5 AU on July 1, 2003. In both diagrams, the vernal equinox is to the right along the horizontal axis. Images by Paul Chodas (NASA/JPL).

the Sun, not much further than Neptune (Fig. 5.3). Many have sizes of 100 to 500 km, but the biggest so far is 2004 DW at 1400–1600 km. Indeed, Pluto, at 2200 km, was soon recognized to be simply one of the largest of these objects. There are now thought to be about 70 000 KBOs larger than 100 km diameter in the observable region of the Kuiper Belt.[12]

At the other end of the size range, there may be as many as 2.8 billion $D > 1$ km sized comets in the Kuiper belt with a steep differential size distribution $\alpha \sim 4.0 \pm 0.5$,[13] enough to replenish the population of short-period comets in the inner solar system. Most mass is in the smaller 0.2–20 km sized objects.

The Kuiper Belt has a group of objects trapped in the 2:3 mean-motion resonance with Neptune (Fig. 5.4). As a result, they never approach the planet close enough to be ejected. These are called *Plutinos*, after its main object Pluto. The resonance is also an efficient dust particle trap.[14]

Gerard Kuiper himself came to the idea of a Kuiper belt by believing that Pluto may be a giant comet. Although this is true, Kuiper based his hypothesis on the incorrect data that the density of Pluto was a low 0.1 g/cm^3, the same low density as he expected comets would have. We now believe that both are closer to 1 g/cm^3.

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[12] D. Jewitt, From Kuiper Belt Object to cometary nucleus. *ESA SP* **500** (2002), 11–19.

[13] W. F. Bottke, A. Morbidelli, R. Jedicke *et al.*, Debiased orbital and absolute magnitude distribution of the near-Earth objects. *Icarus* **156** (2001), 339–433.

[14] E. K. Holmes, S. F. Dermott and B. Å. S. Gustafson, Dynamical evolution of dust particles in the Kuiper disk. *ESA SP* **500** (2002), 43–46.

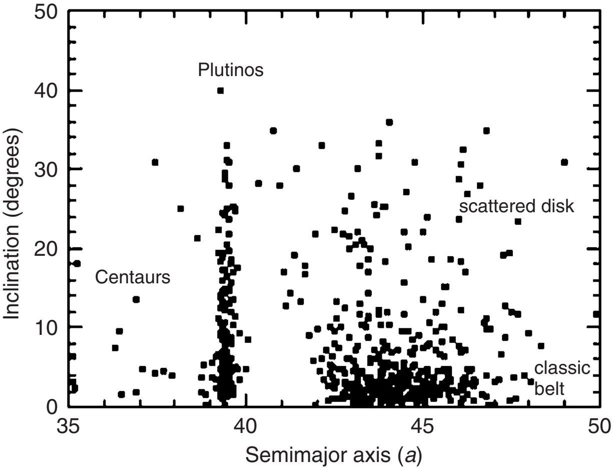

Fig. 5.4 **KBOs** discovered prior to July, 2004 in a diagram of *i* versus *a*. Different populations are marked.

> Pluto is so large that it is spherical with a top layer of volatile ices (nitrogen and methane), overlaying the less volatile water ice. Like Pluto, many Kuiper-belt (and Oort cloud) objects are binaries. Pluto's moon Charon is smaller and does not have volatile ices on top.[15]

Many comets have been found outside the reach of Neptune, between 48 and 52 AU, in a structure that resembles Kuiper's original remnant of a planetary disc. This is called the *Classical Kuiper Belt* containing some 47 000 comets. Because the main planets have not much influence on these objects, they are in relatively stable orbits.

The source of the short-period comets is a structure further out: the *scattered disk*, a thick torus with an inner edge near 35–40 AU ($q \sim 35$ AU), containing more than 1.2 billion comets >1 km in size, and some 30 000 larger than 100 km. The "scattered disk objects" (SDO) have elongated orbits ($a > 50$ AU, high e) that can be unstable. The disk evolved as a consequence of perturbations by Neptune, either in a progressive process of order 1 billion years, or during planet formation. Passing stars or an early proto-planet could also scatter comets and might better explain the outer edge of the classic Kuiper Belt at $a = 48$ AU. This is being investigated. It is not known how far the Kuiper Belt extends beyond this distance. Comets beyond 48 AU appear to be on perturbed noncircular orbits.

The Kuiper Belt was initially 100 times more massive than today, with planetary perturbations gradually eating away the inside parts, causing a steady stream of

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[15] Z. Sekanina, Detection of a satellite orbiting the nucleus of comet Hale–Bopp (C/1995 O1). *Earth, Moon Planets* **77** (1997), 155–163.

comets to come our way. Collisions, too, can perturb the comets inward, and can lead to much dust being created.

Comets are called *Centaurs* once they are found with a perihelion just outside of Jupiter's orbit and an aphelion just inside of Neptune's orbit. There may be some 10 million Centaurs with diameters larger than 100 km, most of which are scattered out of the solar system by the giant planets within a million years. One of those every thousand years makes it into the inner solar system to become a Jupiter-family comet.

5.4 Reservoir of long-period comets: the Oort cloud

It was long known that long period comets arrived at Earth on very elongated orbits from all directions, including orbits that moved against the direction of motion of the planets (retrograde). After correcting the orbital elements measured near Earth for the earlier perturbations by the planets, *Elis Strömgren*[16] published the first list of "original" orbits, which lacked the hyperbolic orbits that were predicted by the then popular theory of *Pierre Simon Laplace* (1749–1825) who had thought that comets were captured from interstellar space. Instead, the comets moved on elongated elliptical and (nearly) parabolic orbits. *Ernst Öpik*[17] found that elongated elliptical orbits are stable against the perturbations from nearby stars, unless their aphelion was beyond $Q = 100\,000$ AU. It was Dutch astronomer *Jan Hendrik Oort* (1900–1992) who in 1950 first formulated the idea of a Sun-bound reservoir continuously supplying new comets (Fig. 5.5).[18] Oort found that all well observed "new" comets used to have their farthest point at a distance of around $Q = 50\,000$ AU, ranging from 6000 to 90 000 AU, or out to one third the distance of the nearest star.[19] He also found no preferential direction of arrival and concluded there had to be a spherical cloud of comets that supplied a steady stream of new objects to the inner solar system (Fig. 5.6). This is now called the "Oort cloud" of comets.

There may be 1 trillion comets in that cloud with $D > 1$ km with a total mass of a few times that of Earth, originally evenly distributed between the inner and outer Oort cloud. The first comet still fully in the Oort cloud was discovered on March 15, 2004, it is called "Sedna" after the Inuit goddess who rules over the seas. Sedna was discovered close to perihelion when it was at 90 AU from the Sun. It is a slow rotator, between 20–50 d. This comet is big, 1200–1600 km in diameter. Long-period comets can be very big!

"New" comets represent only the easily perturbed outer regions of a much larger reservoir. The tidal force of our Galactic plane is the main cause of those perturbations and is effective in perturbing comets only for those in elongated orbits with semimajor

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[16] E. Strömgren, *Publ. Obs. Copenhagen* **19** (1914), 187.

[17] E. J. Öpik, Note on stellar perturbations of nearly parabolic orbits. *Proc. Am. Academy Arts Sci.* **67** (1932), 169–183.

[18] H. Rickman, Dynamics of meteoroid parent bodies: a conceptual history. In *Meteoroids and Their Parent Bodies*, ed. J. Stohl and I. P. Williams, 1992, pp. 83–92.

[19] J. H. Oort, The structure of the cloud of comets surrounding the Solar System and a hypothesis concerning its origin. *Bull. Astron. Inst. Netherlands* **11** (1950), 91–110.

Fig. 5.5 Jan Hendrik Oort at his 90th birthday, as I remember him. Photo: Sterrewacht Leiden.

axis $a > 10\,000$ AU, leaving the inner Oort cloud of objects with $a < 10\,000$ AU untouched. That inner Oort cloud supplies the outer Oort cloud with new comets over the age of the solar system.[20]

The origin of the Oort cloud dates back to the time of the origin of the solar system in the region where the giant planets were formed, where planetesimals accumulated into comets and planets. During close encounters, about 3%–10% of comets in the Uranus–Neptune region were thrown in elongated orbits, while a smaller fraction of comets survived collisions with early versions of Jupiter and Saturn. Because there were more comets closer to the Sun, most Oort cloud comets may have come from near Jupiter. Once in an elongated orbit, small perturbations by nearby stars and

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[20] J. A. Fernández, Dynamics of comets: recent developments and new challenges. In *Asteroids, Comets, Meteors 1993*, ed. A. Milani *et al.* (Dordrecht: Kluwer, 1994), pp. 223–240.

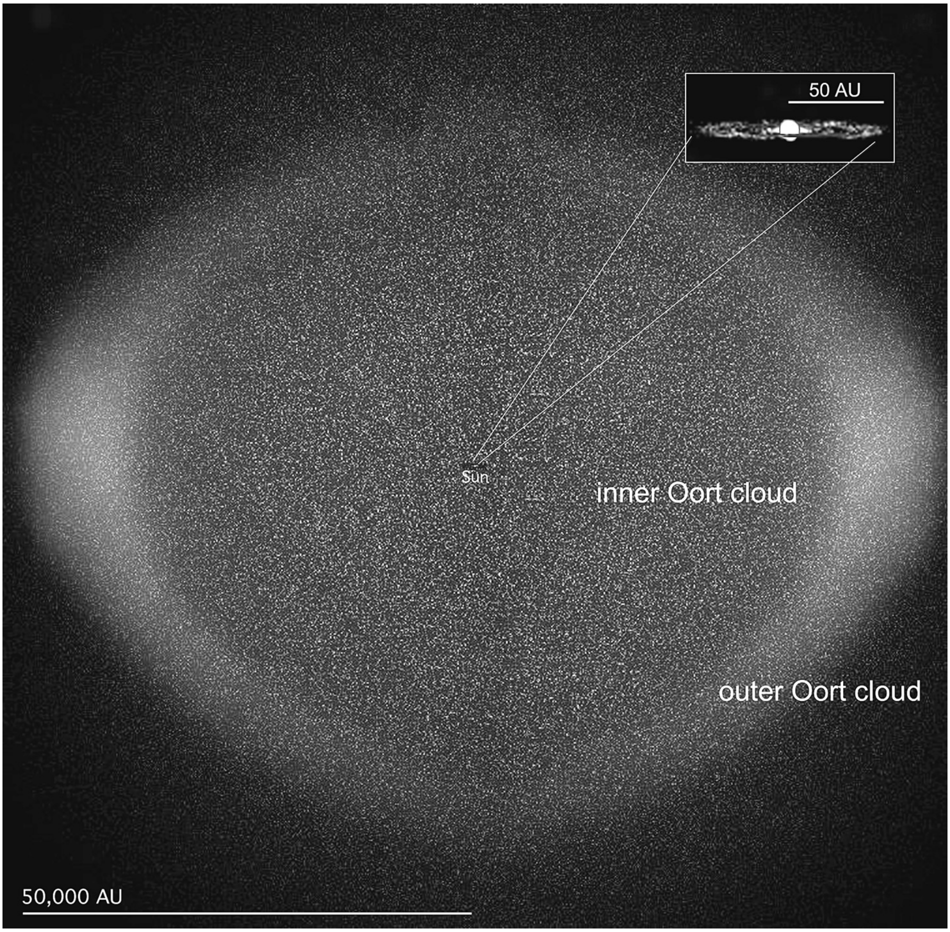

Fig. 5.6 Artist impression of the Oort cloud. This diagram shows a region that is 100 000 AU across. At this scale, the Kuiper Belt is very small.

molecular clouds could increase their perihelion to safe distances and put the comet in cold storage for the next 4.5 billion yr until, one day, the orbit was perturbed enough to bring it back to those now fully grown giant planets and ultimately into the inner solar system. There, ices would evaporate and a new long-period comet would excite observers on Earth.[21]

[21] J. A. Fernandez, The formation of the Oort cloud and the primitive galactic environment. *Icarus* **129** (1997), 106–119.