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

[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.

[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.

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Peter Jenniskens
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More information

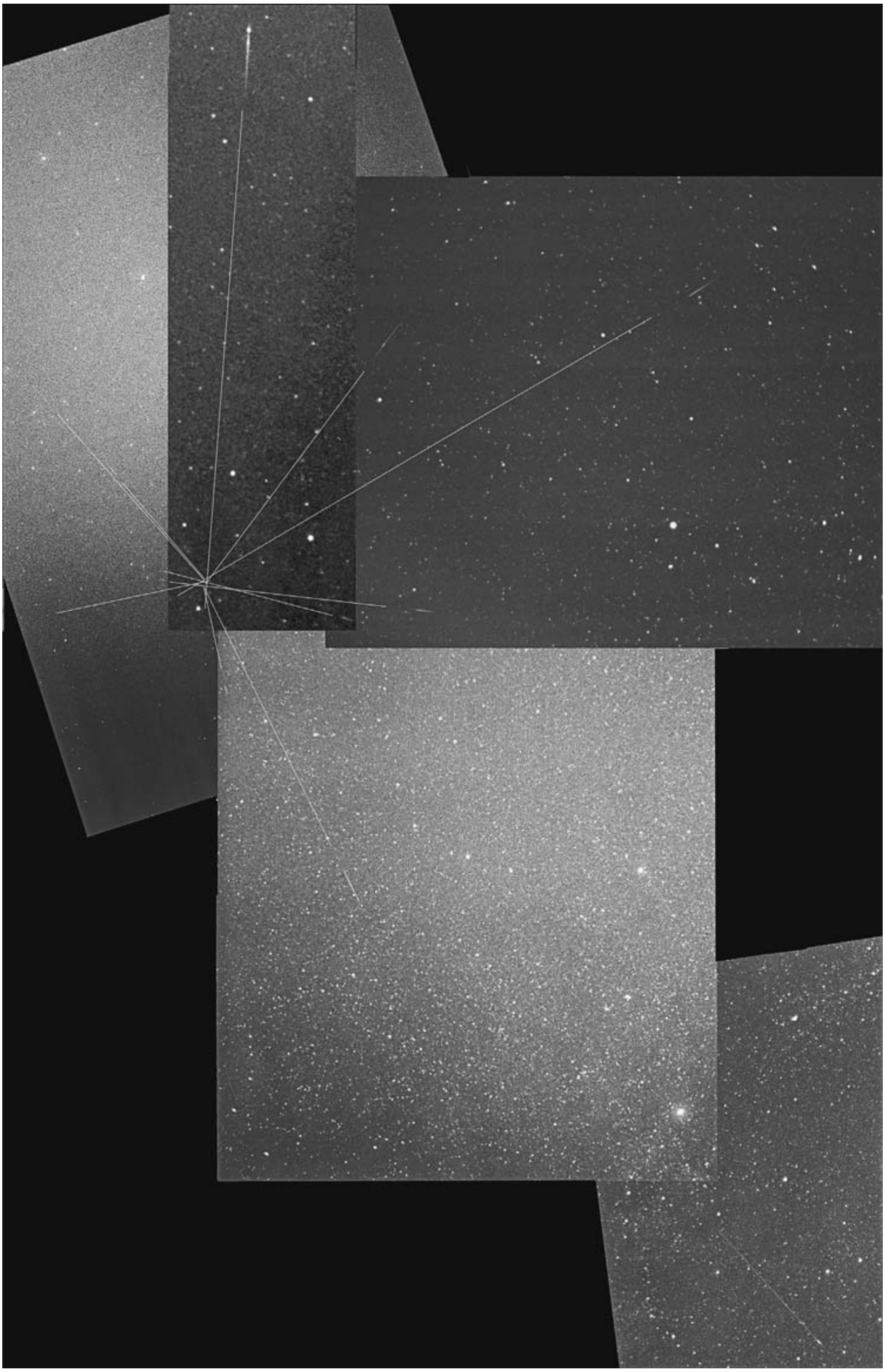

Fig. 1.1 The "radiant" of a meteor shower is the point in the sky from where the meteors appear to radiate, the head of Draco in this compilation of photographs of the 1985 Draconid outburst by members of the *Nippon Meteor Society*.

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.

[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).

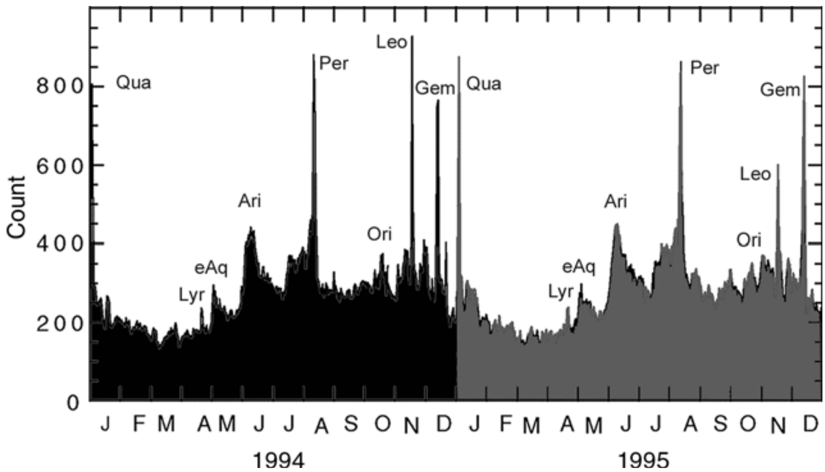

Fig. 1.2 Rate hikes in the daily count of meteors in the years 1994 and 1995, measured by Ilkka Yrjölä of Kuusankoski, Finland, by means of counting reflected radio signals from far away TV or radio stations. Note how the rates repeat year after year.[12]

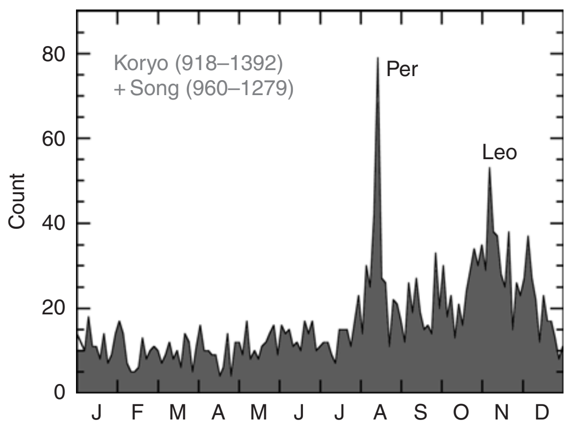

Fig. 1.3 Daily variations in meteor activity in the Middle Ages as reflected in the total daily number of shower reports from the Chinese Song and Korean Koryo dynasties, gathered by Sang-Hyeon Ahn.[13] Note the absence of the now prominent Quadrantid (Boo) and Geminid (Gem) showers.

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

[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

[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

[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

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.

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.