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Observation and interpretation of the Leonid meteors over the last millennium

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Abstract
With a possible 'storm' of Leonid meteors due in 1998 or 1999 November, interest in the Leonids is once again at a peak. The history of the Leonids is of particular importance, not only because they are closely associated with the origins of meteor science, but also because historical observations extending back a millennium are a substantial aid in increasing our knowledge of the Leonid meteor stream. Leonid history is thus a prime example of applied historical astronomy. In this review paper, we recount the origins of meteor science with the Leonids, the discovery of the historical observations and their scientific and cultural interpretations, and the application of this information to characterize the meteor stream and to predict the strength of the 1998-1999 event. These predictions are now of more than passing interest, as meteor storms pose a potential threat to spacecraft.

Key words: *comet, Leonids, meteor, meteor stream, solar system*

1 INTRODUCTION

Of the classes of solar system objects known today, meteors were among the last to be recognized as astronomical in origin. The wandering planets had been known since antiquity; comets were recognized as astronomical rather than meteorological after Tycho Brahe and others placed the great comet of 1577 beyond the Moon; the abundance of circumplanetary objects became known with Galileo's discovery of the Jovian satellites in 1610; and Giuseppe Piazzi discovered the first asteroid on the first day of the 19th century, 1801 January 1. If one considers the recently-detected Kuiper belt objects and the supposed Oort cloud objects to constitute new classes of solar system bodies, like the meteors discussed here, they have a likely cometary connection; they are believed to be the sources of short-period and long-period comets rather than cometary debris. Oort cloud and Kuiper belt objects, however, remain at a safe distance until they are perturbed into the inner solar system, giving us not only cometary phenomena, but also eventually the meteor phenomena described here.

The phenomenon of 'shooting stars' has been widely observed throughout history; catalogues of meteors record observations dating back at least to the 7th century BC, and they were, of course, observed long before that. The Roman poet Virgil, in Book I of the *Georgics*, ll. 365-367 (30 BC), wrote

Oft you shall see the stars, when wind is near
Shoot headlong from the sky and through the night
Leave in their wake long whitening seas of flame

Some have even claimed that meteor storms and larger cometary debris have had a strong impact on historical events (Bailey, 1996; Bailey *et al.*, 1989; Clube, 1996; Clube and Napier, 1990). Although the suspicion that meteors were of cosmic origin dates at least to Edmond Halley in the 18th century (Hughes, 1982), it was not until 1863 that they were definitely proven to be astronomical. This proof was based largely on observations of the Leonid meteors, so-called because their 'radiant point' was in the constellation Leo. The celestial origin of the Leonids, the determination of their periodic nature, the recognition that they resulted from an orbiting stream of objects, and the identification of this stream with a parent comet, are all landmark events that take on added significance because they represent the origin of the relatively-recent science of meteor studies. Although the 'August meteors' (now known as the Perseids) also played a concurrent role (Littman, 1996), they were not so important as the 'November meteors' (later known as the Leonids), which periodically tended to storm, and thus demanded an immediate explanation.

Since the recognition of their celestial origin in the 19th century, records of Leonid observations have been discovered over the last millennium, dating back at least to AD 902. Historical records of meteors in general are of more than passing interest; indeed, they have proved essential to meteor astronomy by making possible conclusions about the orbits of the meteor streams and their parent bodies. They were of critical importance to the birth of meteor science in the 19th century, and they remain no less important today.

2 THE LEONIDS IN THE LAST TWO CENTURIES

It was the Leonid storm of 1799 November 11-12, observed by the German naturalist Alexander von Humboldt among others, that first established the simultaneous geographical extent of the meteor phenomenon. From his location while on travel in Cumana, east of Caracas, von Humboldt wrote that towards the morning of November 12, after half past two, "... thousands of bolides and falling stars succeeded each other during four hours. Their direction was very regularly from north to south ... All these meteors left luminous traces from five to ten degrees in length." (von Humboldt and Bonpland, 1818:331). Curious as to how widespread the phenomenon was, von Humboldt gathered reports from South America and elsewhere. The result was that meteors were reported across 90 degrees of longitude from South America to Germany, and across 60 degrees of latitude from South America to Greenland. Von Humboldt also heard reports of a similar event in South America in 1766. Significant meteor showers are possible in years preceding and following meteor storms; Steel (1998) has argued that a noteworthy Leonid shower in England on the night of 1797 November 12/13 may have inspired Samuel Taylor Coleridge's *The Rime of the Ancient Mariner*, one of the greatest poems of the English language.

The geographic extent of the 1799 storm was a good clue that the phenomenon might be celestial, but the origins of meteor studies awaited the great storm of 1833.

2.1 The Leonids and the Origins of Meteor Studies

Although a storm of meteors occurred in 1832 in eastern Europe and the Middle East, only the 1833 storm inspired astronomers to action. The latter meteor storm peaked in the Eastern part of North America (Figure 1), and it is no coincidence that this was the birthplace of modern meteor studies, though there were antecedents (Hughes, 1982). Denison Olmsted (Figure 2), Professor of Mathematics and Natural Philosophy at Yale University in New Haven, Connecticut, was the crucial figure in this birth. His connection to meteor studies has been detailed in Hoffleit (1992:24-32) in the context of his work at Yale. Olmsted (1834:363) captured the uniqueness of the 1833 November 12/13 event when he wrote

> Probably no celestial phenomenon has ever occurred in this country, since its first settlement, which was viewed with so much admiration and delight by one class of spectators, or with so much astonishment and fear by another class. For some time after the occurrence, the 'Meteoric Phenomenon' was the

principal topic of conversation in every circle, and the descriptions that were published by different observers were rapidly circulated by the newspapers, through all parts of the United States.

His interest ignited by the phenomenon, Olmsted collected and published in *The American Journal of Science and Arts* twelve descriptions of the event as seen from Massachusetts to Georgia. From these and other sources he collated data relating to weather, time and duration, number, variety, sound, and apparent origin. After

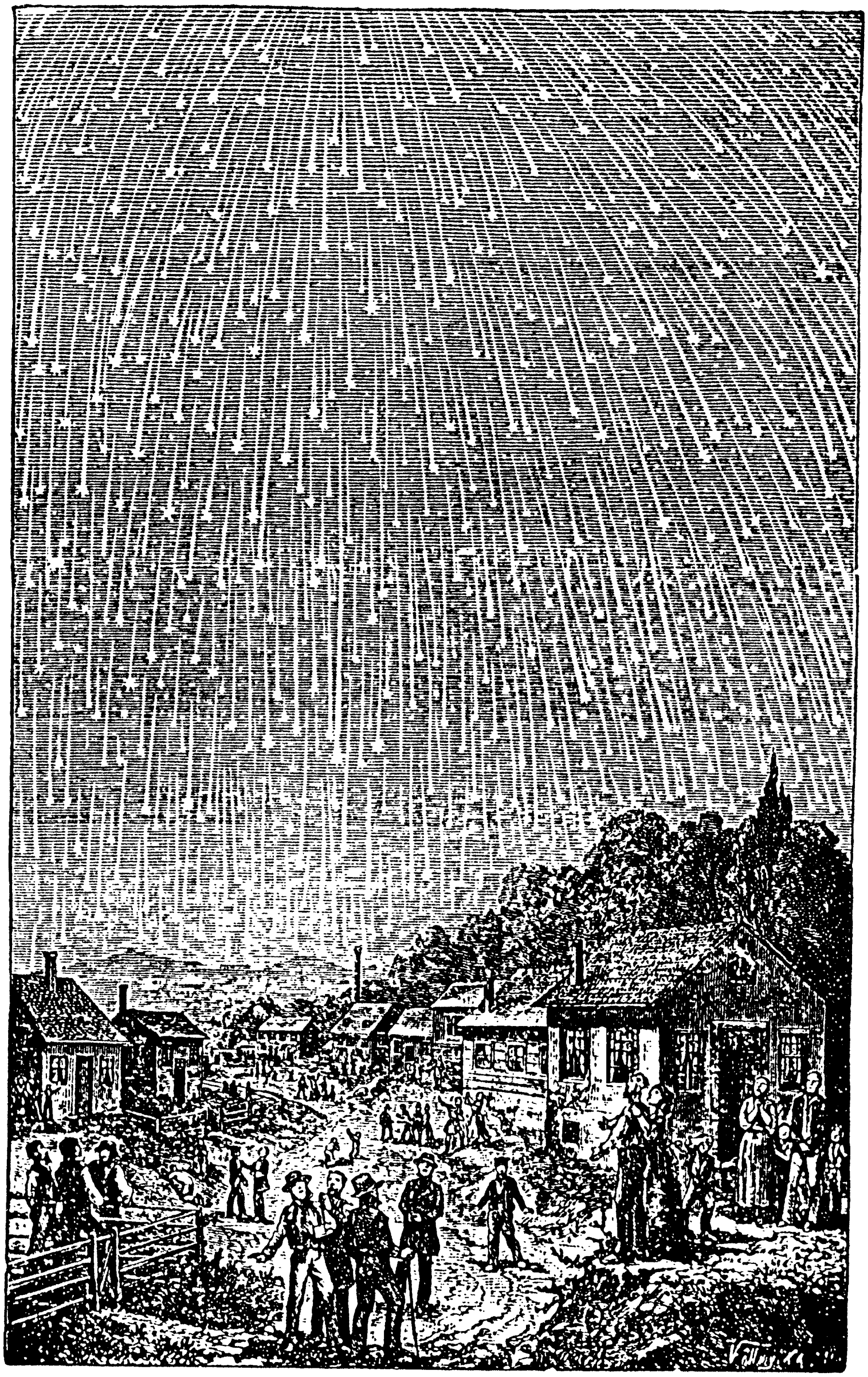

Figure 1. This view of the 1833 Leonid storm, probably the most widely-seen depiction of a meteor event, first appeared in the 1880s. It was produced by Karl Jauslin (1842-1904) and engraved by Adolf Vollmy (1864-1914). See Hughes (1995) for the history of the illustration.

Figure 2. Denison Olmsted, 1791-1859. (Courtesy Dorrit Hoffleit and Yale University Archives)

considering accounts of other meteor showers, Olmsted concluded that the meteors of 1833 originated beyond the Earth's atmosphere, became luminous upon entering the atmosphere at high velocities up to four miles per second, and "appeared to proceed from a fixed point in the heavens ... Those who marked its position among the fixed stars, observed it to be in the constellation Leo, in which it appeared stationary, accompanying that constellation in its diurnal progress" (Olmsted, 1834:394). With that statement, confirmed by the independent accounts of other observers during the storm, Leo was established as the 'radiant' of these meteors. From this time, increasingly the 'November meteors' were referred to as the 'Leonid meteors'.

Olmsted (1834:172) also conjectured that

> ... the meteors of Nov. 13th consisted of portions of the extreme parts of a nebulous body, which revolves around the sun in an orbit interior to that of the earth, but little inclined to the plane of the ecliptic, having its aphelion near to the earth's path, and having a periodic time of 182 days, nearly.

Though Olmsted even identified the nebulous body as possibly a comet, he was wrong in believing that its orbit was between the Earth and the Sun. Thus, Olmsted is generally credited with establishing the Leonid radiant, and beginning the study of meteors as a science. Alexander C Twining, a civil engineer at West Point, New York, who published his ideas in the same journal in 1834, is often also given credit for determining the radiant point, and the same claim is even made for von Humboldt (Hughes, 1982). One may conclude that there is nothing like an impressive natural phenomenon to stimulate scientific thinking, at least if cultural conditions are conducive to such thinking. And in the United States in the 1830s, science was budding into a much more substantial enterprise, as exemplified by the *American Journal of Science and Arts* itself and a variety of other activities (Dupree, 1957; Struik, 1962).

The subsequent history of meteor showers and their eventual connection with comets has been recounted in Yeomans (1991:188-201), but we may here summarize the highlights based upon the original sources. Despite Olmsted's conclusion of a cosmic origin for meteors, even that much was not as yet certain in the first half of the 19th century. So great an authority as Brussels Observatory Director, Lambert-Adolphe-Jacques Quetelet, equivocated in the chapter on meteors in his influential *Sur la Physique du Globe* (Quetelet, 1861), causing Hubert A Newton (1863) to insist that Quetelet's own chapter gave a very strong argument that star-showers, and probably sporadic meteors as well, "... are caused by the entrance into our atmosphere of bodies revolving
about the sun."

The clinching argument for the cosmic origin of meteors came when Newton (Figure 3) determined that the cycle repeated in intervals of sidereal years, not tropical years. Hoffleit (1992:47-56) has also placed Newton's work in the context of 19th century astronomy at Yale University, where he was a Professor of Mathematics. If meteors were due to terrestrial phenomena such as magnetism, heat, or electricity, he reasoned, meteor events should repeat in intervals of the tropical year. But Newton (1863) cited historical dates of known meteor showers to "... show quite clearly that the true period is not widely different from the sidereal year." Moreover, based upon his historical data, Newton calculated the interval between Leonid showers to be 33.25 years, and predicted that the meteor shower would return in 1866. Finally, Newton speculated that the meteor shower was caused by small bodies in elliptical orbit around the Sun. He determined five possible periods for the orbit of these bodies, including 33.25 years, but did not calculate a definitive orbit.

Newton's prediction proved true, but the peak of the 1866 storm occurred in Europe rather than in the United States. And sure enough, this time astronomers in four European countries were inspired to solve the riddle of the orbit of the meteor stream and its parent body. The largely independent and almost simultaneous work in 1866-1867 of John Couch Adams in England, Giovanni Schiaparelli in Italy, U J J Le Verrier in France, and Theodor von Oppolzer and C F W. Peters in Germany, are often cited together in this respect. But in his paper 'On the Orbit of the November Meteors', Adams (1867), famous for his earlier work leading to the discovery of Neptune, provides a contemporary account of the chronology and a hint of the international rivalry that must have taken place during a few crucial months in 1866-1867.

Adams tells us that Schiaparelli, the Director of the Milan Observatory, showed in four letters to Angelo Secchi (Schiaparelli, 1866-67) that the orbits of meteor streams around the Sun are very elongated, as are those of the comets, and that "... both these classes of bodies originally come into our system from very distant regions of space." More specifically, in Schiaparelli's last letter, dated 1866 December 31, he remarked on the very close agreement in the orbital elements of the August meteors (now known as the Perseids) and Comet II 1862. To the Italian astronomer thus goes the credit of showing that the comet now known as 109P/Swift-Tuttle is the source of the Perseids. Schiaparelli also attempted to find a comet with elements similar to those of the November meteors, but failed because the inaccurate radiant point he used yielded erroneous orbital elements for the meteor stream.

According to Adams, on 1867 January 21, Le Verrier (1867) communicated to the French Academy of Sciences a theory similar to Schiaparelli's, but with more accurate elements, including a period of 33.25 years. It was left to Peters (1867) of Altona, Germany, to notice one week later that Le Verrier's elements agreed closely with a certain Comet I 1866, discovered by Tempel 1865 December 19, and which passed perihelion in early 1866 January. The elements of what is today known as Comet 55P/Tempel-Tuttle had been determined by Theodor von Oppolzer (1867), who calculated a period of 33.18 years for the comet. A few days after Peters's announcement, Schiaparelli (1867) independently noticed the same agreement between Le Verrier's elements of the meteor stream and the comet. Thus, in the space of only one month, the connection that we accept today between comets and meteors was established beyond doubt.

Figure 3. H A Newton, 1830-1889. (Courtesy Dorrit Hoffleit, Yale University)

Adams's own paper appeared in the 1867 April 12 issue of *Monthly Notices of the Royal Astronomical Society*. Referring to the papers of 1863 and 1864, where Newton identified 13 displays of the Leonids, Adams recalled Newton's estimate of 33.25 years for the recurrence of the displays. He also recalled Newton's conclusion that the November meteors "... belong to a system of small bodies describing an elliptic orbit about the Sun, and extending in the form of a stream along an arc of that orbit which is of such a length that the whole stream occupies about one-tenth or one-fifteenth of the periodic time in passing any particular point." (Adams, 1867:248). In one year, Newton had concluded, this group must revolve about the Sun in 2 ± 1/33.25 revolutions, or 1 ± 33.25 revolutions, or 1/33.25 revolutions. In other words, the period corresponded to either 180 days, 185.4 days, 354.6 days, 376.6 days, or 33.25 years. Adams's own contribution was to show that the actual period was the last of these, 33.25 years. This he did by first assuming that period, and showing that during this time the longitude of the node would be increased by 20 arc seconds by the perturbation of Jupiter, seven more arc seconds by Saturn, and one arc second by Uranus, for a total of 28 arc seconds compared to the 29 arc seconds actually observed. This "... remarkable accordance between the results of theory and observation ..." allowed Adams to then determine independently elements very similar to those of Le Verrier.

We thus see during the 19th century the progression in understanding of meteors from establishing the radiant and a probable celestial origin in 1834, to a definite celestial origin and an accurate interval between showers with Newton (1863), a definite period for the meteor stream (Adams, 1867), and finally identification of meteors with comets as parent bodies, first by Schiaparelli (1866-1867), who identified the August Perseids with the comet now known as 109P/Swift-Tuttle, then by Peters (1867), who identified the November Leonids with the comet now known as 55P/Tempel-Tuttle. Only a few months later, the Irish astronomer, G Johnstone Stoney (1867), wrote a paper on the connection between meteors and comets, the beginning of a long series of such studies that has continued to the present day. Further significant showers in North America, in 1867 and 1868, which Mason (1995) classifies as storms, inspired E L Trouvelot to a memorable artistic rendering (see Figure 4).

Figure 4. Trouvelot's painting of the November 13/14, 1868 Leonid meteor storm. Trouvelot himself observed the event from midnight to sunrise. The drawing shows all forms of meteors observed during the night, not necessarily appearing simultaneously. Trouvelot (1882) describes the drawing in detail. (Courtesy Dorrit Hoffleit and Mt. Holyoke College Library)

But there was still more to learn about the Leonids, in particular about the distribution of the material in the meteor stream. Just when astronomers thought they had a good understanding of the November meteors, the predicted storm of 1899 failed to appear. In 1925, the astronomer Charles Olivier called this "... the worst blow ever suffered by astronomy in the eyes of the public ..." (Olivier 1925:38). This is a public relations problem which astronomers can still sympathize with today.

2.2 The Twentieth Century

Leonid studies in the 20th century were marked by good showers in 1930-1932, the strongest storm witnessed in modern times in 1966, and steady progress in understanding meteors and meteor streams with the help of new techniques of observation.

The 1930-32 showers were best seen from North America, and exhibited rates of about 240 per hour (Kronk, 1988; Mason, 1995). Following the disappointments of 1899 and 1930-32, Lovell (1954:338) concluded that "It now seems certain that the main part of the Leonid orbit has been removed from the Earth's orbit by successive perturbations, and the recurrence of the tremendous meteoric storms of the Leonids in the future seems unlikely."

Many were surprised, then, when a storm was visible in Europe in 1965, and even more so when an estimated 100,000 meteors per hour were observed at the peak of the 1966 Leonid storm in the south-western United States (Kronk, 1988; Mason, 1995; Milon, 1967). The descriptions were less hysterical than in the previous centuries, but the event was clearly awe-inspiring nonetheless. "The sky began to rain shooting stars," one observer wrote. "By 11:30 there were several hundred a minute. A quarter-hour later, the meteors were so intense that we were guessing how many could be seen in a one-second sweep of the observer's head. The fantastic rate of 40 per second was reached at 11:54, difficult to gauge but the consensus of our observing group." (Great Leonid meteor shower ..., 1967:5).

Visual, photographic and radar techniques helped make the 1965-66 storms the most studied on record (Figure 5). The techniques available by that time are systematically summarized in Millman and McKinley (1963). The development of radar techniques, which detect the ionization trail of meteors, was intimately connected with the development of radar in World War II (Lovell, 1954; Butrica, 1996). Pioneered by the group of radio astronomers led by Bernard Lovell at Jodrell Bank, the 'radio-echo' technique not only gave a scientific record of observations, but for the first time allowed observations in daylight. The technique also refined Newton's thesis that meteors were of cosmic origin. By showing there was no significant hyperbolic velocity component, meteors were determined to be orbiting the Sun rather than of interstellar origin.

Photographic techniques were systematically used by the Harvard University projects led by Fred Whipple during the 1930s and 1940s (Lovell, 1954), and became widely successful with the development of the Baker Super Schmidt cameras. The primary purpose of these cameras, developed by James G Baker in the 1950s, was to give excellent image-definition over a wide field up to 55 degrees. The context of Whipple's work is described in Doel (1996).

Our modern view of the Leonids, shaped over the last two centuries, thus envisions them as a stream of particles in the orbit of Comet 55P/Tempel-Tuttle (Figure 6), a retrograde orbit (compared to Earth's) that has its aphelion just beyond the orbit of Uranus. The comet has spewed out these particles along its orbit in a complex distribution pattern, the outlines of which were recognized already at the end of the 19th century by Stoney and Downing (1899). Some, now widely scattered all along the orbit of the comet, are called the clino-Leonids and produce the weak annual Leonid showers. But a dense swarm of particles, known as the ortho-Leonids, remains within a few astronomical units of the comet. The apparent weakness of the clino-Leonids and the density of the ortho-Leonids are anomalous for such an old meteor stream, and Williams (1997) has proposed that this may be due to perturbations by Uranus. In any case, it is

Figure 5. Photograph of Leonid storm of 1966 showing the radiant in Leo. Regulus is the bright star at the bottom of the sickle. This 3.5 minute exposure was taken from Kitt Peak, Arizona. (Photograph by Dennis Milon, distributed by Scott Milon)

the length of the dense swarm that gives us the chance for greatly-increased activity in November, over several sequential years. The width of the narrow swarm, however, is perhaps only 35,000 kilometres, so that the activity will last only a few hours - and will be visible only for that part of the Earth that happens to be turned in the right direction, speeding head-on into the meteor stream. We observe the meteors as they ignite in the atmosphere at an average height of 70-110 kilometres.

A great deal of work has subsequently gone into the study of meteors, and the volumes of Kresak and Millman (1968) and Stohl and Williams (1993) are representative of the research that has refined our knowledge of the nature of meteor streams and their relationship to comets.

2.3 Assessment: Why the Nineteenth Century?

We may well ask why meteor science began only in the 19th century, and why meteors took so long to be recognized as astronomical. For most of the period prior to the 17th century, the answer is that acceptance of the celestial-terrestrial dichotomy of Aristotelian cosmology prevented the identification of meteors as cosmic in origin. Aristotle believed the heavens were unchangeable, and that any observed change had to be Earthly or meteorological. Thus, comets were long held to be atmospheric phenomena, and there was a crisis when Tycho Brahe proved the comet of 1577 to be located beyond Earth.

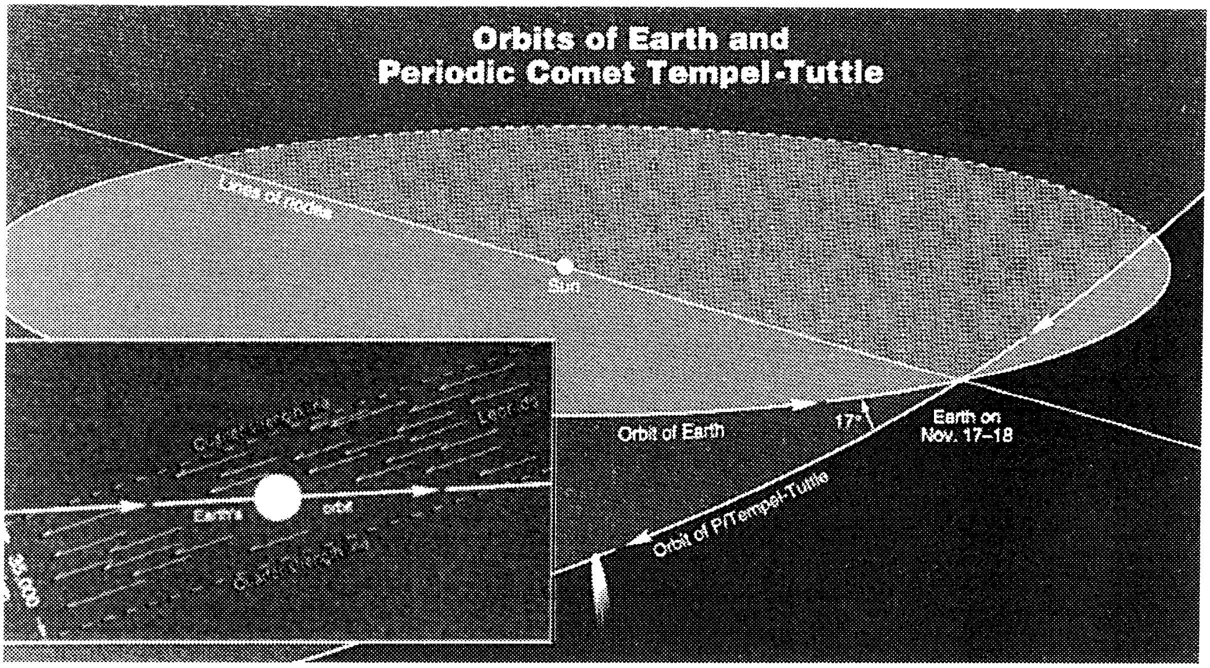

Figure 6. Orbits of Earth and Comet 55P/Tempel-Tuttle. Because the orbit of the comet is retrograde compared to Earth's orbit, Earth moves head-on into the stream. The particles are scattered all around the orbit of the comet, but are particularly dense within a few astronomical units of the comet. The width of this dense swarm is only about 35,000 kilometres. (By permission of Sky Publishing Corporation)

On the assumption that a major storm was necessary to trigger a new explanation of meteors rather than the few sporadic meteors occasionally observed, one may wonder about the other Leonid storms during and after the 17th century. We note from Table 1 that the 17th century Leonid storms of 1601-02 and 1666 were visible only in China, where the Scientific Revolution under way in Europe had yet to take place (for Chinese natural philosophers still laboured under Aristotelian assumptions). The 1698 Leonid storm, by contrast, was visible in Europe and Japan. One might have thought this would trigger a search for a celestial origin, at least in Europe, but of this there is no record. And in the 18th century, when Leonid storms were reported in 1766 in South America, and in 1799 in eastern North and South America, astronomy had not yet advanced far enough in those locales to trigger a crisis that demanded explanation in scientific terms.

The storm of 1832, visible in eastern Europe and the Middle East, might have triggered renewed attempts at explanation. In his pioneering account of historical Leonids, Newton (1863) noted that descriptions of the 1832 display were given in many newspapers and scientific journals throughout Europe, and that Le Verrier himself saw them and noted "... it would have taken several hours to count those visible at one instant, supposing them fixed." Why there was not more of an attempt to provide a scientific explanation of this impressive display, in sophisticated Europe, remains a mystery. For whatever reasons, that role was left to the storm of 1833, when fledgling American science, represented by Olmsted and Twining, precipitated the events we have described earlier.

Table 1. Probable Leonid meteor storms excerpted from Mason (1995)

	Date	Where Observed
902	Oct 12-13	Southern Europe and North Africa
934	Oct 13-14	Europe, North Africa and China
	Oct 14-15	
1002	Oct 14-15	China and Japan
1202	Oct 18-19	Middle East and China
1237	Oct 18-19	Japan
1238	Oct 18-19	Japan
1366	Oct 21-22	Europe and China
1532	Oct 24-25	China and Korea
	Oct 25-26	
1533	Oct 24-25	Europe, China, Korea, Japan
	Oct 25-26	
1566	Oct 25-26	China and Korea
	Oct 26-27	
1601	Nov 5-6	China
1602	Nov 6-7	China
1666	Nov 6-7	China
1698	Nov 8-9	Europe and Japan
1766	Nov 11-12	South America
1799	Nov 11-12	Eastern parts of North and South America
1832	Nov 12-13	Eastern Europe and Middle East
1833	Nov 12-13	Eastern parts of North America
1834	Nov 12-13	North America
1866	Nov 13-14	Europe
1867	Nov 13-14	Eastern parts of North America
1868	Nov 13-14	North America
1965	Nov 16-17	Eastern Europe
1966	Nov 16-17	Central/South-west North America

3 HISTORICAL OBSERVATIONS OF THE LEONIDS PRIOR TO 1799

3.1 Early Meteor Catalogues and Cultural Effects of Meteors

The observations over the last two centuries might have been the only Leonid observations known had not scholars begun systematically examining the historical literature. Catalogues of falling stars were compiled before they were studied as groups of particular showers or storms. Among the earliest of these was Adolphe Quetelet's 1839 *Catalogue des Principales Apparitions d'Étoiles Filantes* (Figure 7), which was widely used for subsequent meteor studies. It was followed by the catalogues of Yale librarian and amateur astronomer, Edward Herrick (1841); the Frenchman, Edouard C Biot (1841); the French astronomer and popularizer, Francois Arago (1860); and by Quetelet's own update, in 1861. Biot's catalogue covered 24 centuries of Chinese observations, from 687 BC to AD 1644. Arago's catalogue, in his *Astronomie Populaire*, was entirely a compilation from other catalogues, listed by month, from which the prominence of the August Perseids and the November Leonids was evident, but still unexplained.

But it was only in the 1860s that H A Newton set out to identify Leonid events more systematically, using previous catalogues and the historical record. He found six possible Leonid events (Newton, 1863), including the 1799 and 1833 apparitions described by Humboldt and Olmsted. In 1864 he extended these to 13 Leonid events, dating between AD 902 and 1833 (Newton, 1864). Most of Newton's accounts were cited in previous catalogues, but he took the precaution of going back to the original sources wherever possible.

The identification of these early accounts of the Leonids naturally raises the question of their effect on the cultures of the times, for given the impact of the Leonids in 1833, one can imagine the effect that such storms had on the population in pre-scientific

ACADÉMIE ROYALE DE BRUXELLES.

CATALOGUE

DES

PRINCIPALES APPARITIONS

D'ÉTOILES FILANTES,

PAR

Adolphe

A. QUETELET,

Secrétaire perpétuel de l'Académie Royale et directeur de l'Observatoire de Bruxelles; chevalier des ordres de Léopold, d'Ernest de Saxe et du Christ; correspondant de l'Institut de France; de l'Institut des Pays-Bas; des Académies Royales de Berlin, de Turin, de Naples, de Lisbonne et de Palerme; de la Société Royale astronomique et de la Société météorologique de Londres; de la Société Royale d'Édimbourg; de la Société philosophique de Philadelphie; de l'Académie américaine de Boston; de l'Institut d'Albany; de l'Académie des lyncées de Rome; des Sociétés des sciences naturelles de Genève, de Heidelberg, de Wurzbourg, de Lille, de Nancy, du grand-duché de Bade, de Dresde, etc.

(MÉMOIRE LU A LA SÉANCE DU 8 JUIN 1839.)

BRUXELLES,

M. HAYEZ, IMPRIMEUR DE L'ACADÉMIE ROYALE.

1839.

Figure 7. Title page from Adolphe Quetelet's 1839 catalogue of meteors, among the earliest catalogues of 'falling stars'.

cultures. The 'interpretation' of these early events was not physical, but cultural, political, and religious. Even more than for comets, which appeared relatively calm and distant by comparison, such apparitions were often associated with great, and usually catastrophic, events. This was the case for the earliest of these accounts, in AD 902, which was visible in Southern Europe and North Africa, where Islamic civilization was in full bloom. For this event, Newton (1864:378) translated from the original Spanish of Conde's *Historia de la Dominacion de los Arabes en Espana*, where the dates were based on the Islamic calendar reckoned from the start of the Hegira (AD 622, July 16 or 17):

> In the month Dhu-l-Ka'dah of this same year (289 A.H.) died king Ibrahim bin Ahmad, and that night there were seen, as it were lances, an infinite number of stars, which scattered themselves like rain to right and left, and that year was called the year of the stars.

Dhu-l-Ka'dah is the tenth month of the Islamic calendar. And regarding the same event, from a history of the Saracens:

> In the year 286 [Newton believes it was AH 289, and thus the same year as in the above account] there happened in Egypt an earthquake, on the Fourth Day [of the week], on the 7th of Dhu-l-Ka'dah, lasting from the middle of the night until morning; and so-called flaming stars struck one against another violently, while being borne eastward and westward, northward and southward; and no one could bear to look toward the heavens, on account of this phenomenon. (Newton, 1864:380).

Not only the death of a king and an earthquake, but also the razing of the Italian city of Castellum Lucullanum from fear of the Saracens, the removal of its population to Naples, and various Christian events are associated with this astronomical event, which Newton (1864:381) dates as 902 October 13.

The 934 event, classed as a Leonid storm by Mason (1995), and visible in Africa, China, and a Europe still deep in the so-called 'Dark Ages', was also associated with an earthquake:

> And there was an earthquake, in Egypt, on the third day of Dhu-l-Ka'dah of the year [AH 323]; and flaming stars struck against one another violently. (Newton, 1864:382).

The 1002 event was seen in China and Japan, and refers with some precision to positions of the meteors in the sky:

> Period Khien-ping, fifth year, ninth month, 35th day of the cycle (October 14th) there were seen moreover thousands of small stars, which appeared in the group alpha, gamma, delta Cancri, and went as far as the group lambda, mu, Ursae Majoris. Generally a large star was seen followed by a half score of small stars. Among them were seen two stars as large as a quart measure; these went, one to the star Sirius, the other to the group phi, rho, tau Sagittarii, and vanished. (ibid.).

Had this event been viewed in the Western world, it would undoubtedly have been imbued with millennial fear; even though no catastrophic connection is specified in this account, we may well imagine that such connections were made.

An Arab account of the AD 1202 storm, visible in the Middle East and China, refers to a religious reaction:

> And in the year 599 [AH], on the night of Saturday, on the last day of Muharram, stars shot hither and thither in the heavens, eastward and westward, and flew against one another, like a scattering swarm of locusts, to

> the right and left; this phenomenon lasted until day-break; people were thrown into consternation, and cried to God the Most High with confused clamor; the like of it never happened except in the year of the mission of the Prophet, and in the year 241. (Newton, 1864:383).

The 1366 event, also believed to have been a Leonid storm, was visible in Europe and China. The original source was Duarte Nunez do Liao, *Chronicas dos Reis de Portugal Reformadas* (Lisbon, 1600), and was quoted by von Humboldt in his *Kosmos* (1850), whence Newton (1864:384) took it:

> In the year 1366, and xxii days of the month of October being past, three months before the death of the King Don Pedro (of Portugal), there was in the heavens a movement of stars, such as men never before saw or heard of. From midnight onward, all the stars moved from the east to the west; and after being together they began to move, some in one direction, and others in another. And afterward they fell from the sky in such numbers, and so thickly together, that as they descended low in the air, they seemed large and fiery, and the sky and the air seemed to be in flames, and even the earth appeared as if ready to take fire. That portion of the sky where there were no stars seemed to be divided into many parts, and this lasted for a long time. Those who saw it were filled with such great fear and dismay, that they were astounded, imagining they were all dead men, and that the end of the world had come.

The 1533 Leonid storm is of interest because it was visible not only in China, Korea, and Japan, but also in Europe, where Copernicus was about to shock the world with his *De Revolutionibus*. Newton (ibid.) gives only one account, and it is Oriental:

> Period Kia'tsing, twelfth year, ninth month, the 13th day of the cycle (October 24th) ... from the fourth to the fifth watch (from 2 to 4 am), in the four parts of the heavens, there were innumerable shooting stars, great and small, moving together in straight and oblique lines. This continued until daylight.

One may wonder whether some of the early figures of the scientific revolution in the western world viewed this event.

The 1602 storm, which might have been of interest for the reaction of a scientifically-enlightened individual in western Europe like Kepler, was visible only in China, as was the 1666 event. Even the 1833 storm had cultural implications, for renditions of the falling stars from this storm were used to illustrate the Day of Judgment, an allusion that undoubtedly came to mind for more than a few individuals who observed the event.

The cultural effects of the Leonid meteor storms and other meteor events may be put in context by reference to the claims of Bailey *et al.* (1989), and Clube and Napier (1990), who have suggested that high points in the meteor flux caused by the debris of giant comets may have affected historical events more than we might think. As Bailey (1996:659) most recently puts it, "Episodes of bombardment ... may provide an explanation for periods of global cooling as registered in the historical record, even for the strong interest displayed by most early civilizations in celestial phenomena, providing a possible common origin for myths and legends from around the world." More than that, Clube (1996) speculates that transmutations in human society, documented by historians, such as Spengler and Toynbee, are due to cometary fragmentation events.

One need not fully embrace this stimulating but unproven hypothesis in order to assert that astronomical events, such as the Leonids, have played an important role in cultural history. The question is how great the effect has been, and one can imagine a spectrum of effects through history, depending upon whether the event was a meteor shower, a meteor storm, the fragmentation of a giant comet. or an event of the Tunguska type. The logical extension of this punctuated equilibrium backward through geological time is manifested in the record of major extinctions of terrestrial life, including the one believed to have caused the demise of the dinosaurs.

3.2 Modern Catalogues and the Problem of Interpretation

The pioneering modern catalogue of meteor showers is that of Imoto and Hasegawa (1958), first published in Japanese in 1956. It contained 118 meteor showers recorded in the Orient in the last 25 centuries, including 18 Leonid events. In 1993, Hasegawa updated his earlier catalogue, incorporating Chinese records (Beijing Observatory, 1988; Tian-shan, 1977) and European records (Dall'olmo, 1978). His new catalogue (Hasegawa, 1993) includes 331 meteor showers, 48 of which are Leonid events.

In 1992, Rada and Stephenson examined medieval Arab chronicles, and Kidger (1993) used their data to identify seven possible Leonid events, including one in AD 855, 14 years before a Leonid storm would be due. Kidger remarks that this could have been an anomalously-strong annual Leonid shower, which, if true, would make it the earliest recorded Leonid event yet found. Hasegawa (1996) makes further refinements in the Rada and Stephenson data, based upon the solar longitudes at the time of the meteor shower maximum. In his comprehensive review of all Leonid data, Mason (1995) found 58 Leonid events, including 23 probable storms.

Table 2 summarizes the growth in our knowledge of the historical Leonids. While in 1863 only six historical Leonid events were known, 58 are now on record, thanks to the detective work of many astronomers and historians. Most of that increase has come since 1956, and we can be sure that many more events remain to be discovered. The discovery of meteor events in the historical literature remains a promising field, one that will shed more light on the Leonids as we approach future potential Leonid storms.

Table 2. Growth in knowledge of historical Leonids

Author	Year	No. of Leonid Events Identified
Newton	1863	6
Newton	1864	13
Imoto & Hasegawa	1956	18
Hasegawa	1993	48
Mason	1995	58

As the early accounts given above clearly illustrate, historical accounts of meteor observations are subject to various problems. Not the least of these is dating, including conversions among the calendars of different cultures, an essential determination if an event is to be classified as a Leonid. In classifying an event as a shower or a storm, subjective accounts are not always reliable. Moreover, astronomical considerations must also be taken into account, for the difference between the sidereal year and the tropical year causes a 1.4 day per century delay in the maxima of Leonid events, while the nodal advancement due to planetary perturbations causes another 1.4 day delay per century, giving a total of 2.8 days per century. Thus, as we see in Table 1, the 902 event took place on October 12-13, compared to November 16-17, in 1966, when the last Leonid storm occurred. The data contained in Table 1 are thus a triumph not only of observation, but also of interpretation over the last 130 years.

4 APPLICATIONS OF HISTORICAL DATA

As we have seen, historical observations of the Leonids were used by Newton and others to determine the basic elements of the meteor stream orbit in the 19th century. Such observations continue to be used for modern scientific purposes. The volumes of Kresak and Millman (1968) and Stohl and Williams (1993), for example, illustrate how these observations have contributed to our knowledge of the dynamical and physical nature of meteor streams.

It was Yeomans (1981), however, who used the full range of Leonid meteor shower data from the period 902-1969 to map the distribution of dust surrounding the parent comet Tempel-Tuttle, to predict the strength of the Leonid event in 1998-1999, and to redetermine the orbit of Tempel-Tuttle. Using these historical data, Yeomans graphically presented the dust distribution (Figure 8), and demonstrated that most of the dust resides outside the orbit of the comet, and behind or just slightly ahead of it. This led him to conclude from the position of the dust that radiation pressure and planetary perturbations, rather than ejection processes, control the dynamic evolution of the Leonid stream. Plotting past Leonid events on this graph, Yeomans concluded that "... the likelihood of an unusual Leonid shower event in 1998 and 1999 is very good but by no means certain." (Yeomans 1981:498-499). Certainty cannot be obtained because of the uneven distributions within the larger body of dust.

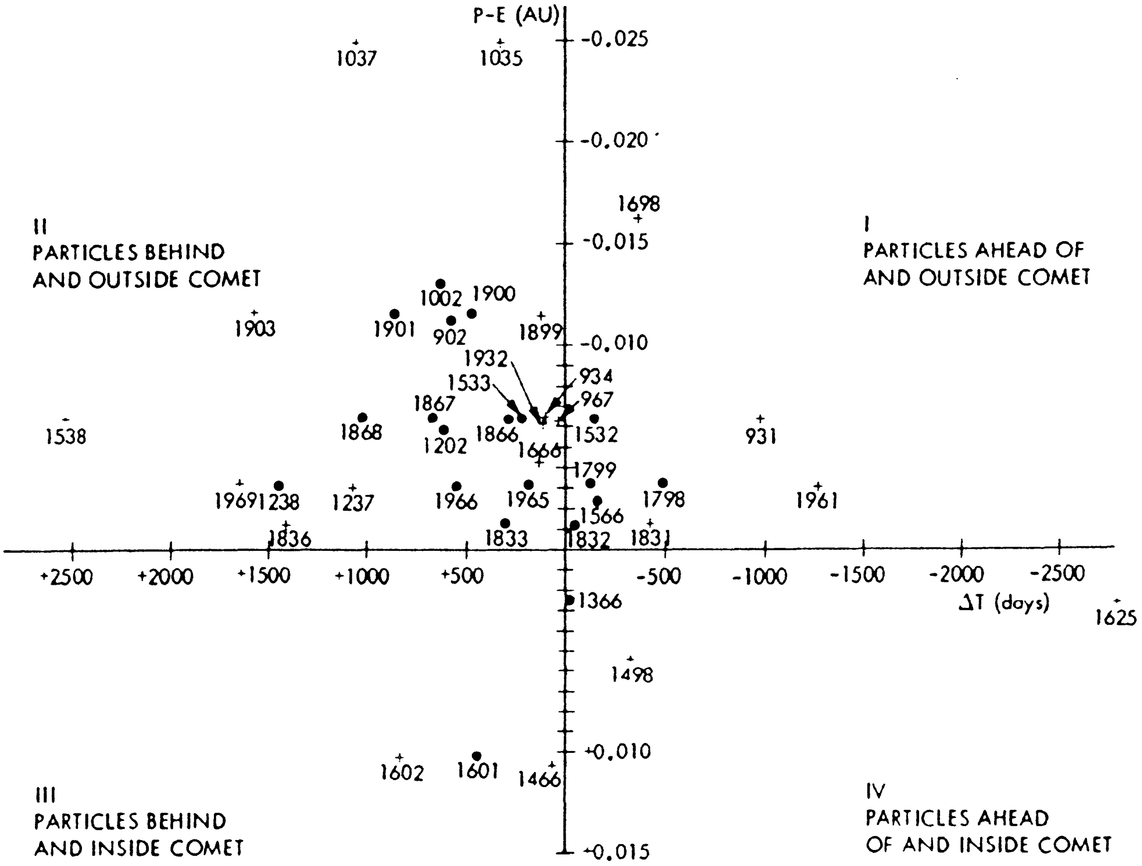

Figure 8. Distribution of dust around Comet Tempel-Tuttle, from the study of Yeomans (1981). The vertical line represents the distance in astronomical units that the Leonid particles were inside or outside the orbit of the parent comet, and the horizontal line gives the times in days that these particles lag or lead the parent comet. A + sign represents a meteor shower, while a filled circle represents a meteor storm. (From *Icarus* **47** (1981), 492-499, by permission of Academic Press, Inc. and D. K. Yeomans)

Mason undertook a similar study of the historical evidence, which resulted in more precise predictions. His study found that "Of the 58 Leonid displays researched, 27 of the 35 outstanding showers, and all 23 meteor storms, have occurred between 750 days before and 1750 days after the parent comet's passage through the descending node ..."

(Mason 1995:219). Of those, "A total of 19 meteor storms took place between 250 days before and 750 days after the comet's nodal passage." (Mason 1995:232). The study also showed that most of the dust was concentrated outside the comet's orbit, where 41 of the 58 documented Leonid events, including 18 of the 23 storms, occurred. Based upon these findings Mason believes the circumstances for 1997-2000 are comparable to those of 1865-1868. He concludes (Mason 1995:234) that there is "... an excellent chance of enhanced Leonid activity ..." between 1996 and 2002. More specifically, "A Leonid meteor storm is most likely, but by no means certain, in November 1998 or 1999 or both, with probable noteworthy showers in 1997 and 2000." (Mason 1995:219). For 1998 November 17, the Leonid events are likely to peak in eastern and central Asia, and in the early morning hours of 1999 November 18, they will peak in eastern and central Europe and in north Africa.

These expectations are being carefully monitored by both amateur and professional astronomers (Rao, 1995). Since 1991, the International Meteor Organization has sponsored a co-ordinated International Leonid Watch (Jenniskens and Butow, 1998; MacRobert, 1995, 1996). Actual observations of the Leonids in the last few years have shown modestly increased activity; both the predictions and observations are updated on the World Wide Web (Jenniskens and Butow, 1998). A large audience attended a Joint Discussion on 'The Leonid Meteor Storms: Historical Significance and Upcoming Opportunities' at the IAU General Assembly in Kyoto in 1997 August, where a variety of observing techniques was also discussed and at least one attendee vividly recalled his observations of the 1966 storm. The concerns, however, are more than academic; in light of the potential Leonid event, a Conference on 'Leonid Meteoroids Storm and Satellite Threat' was held in California in 1998.

Those who view the Leonids as a threat to satellites may hope for little activity, but far more numerous are those who wish to see a rare astronomical event. If it does not materialize, humanity may have to wait a long time for another display equal to the great storms of the past. Mason (1995) concludes that significant Leonid activity during the period 2029-2033 is unlikely. Yeomans *et al.* (1996) go even further, stating that because of planetary perturbations on the Leonid stream, significant Leonid events are not likely for another century after 1999 (Rao, 1996). This is graphically apparent in the plot of minimum distances between Comet Tempel-Tuttle and Earth at the time of the comet's passage through its descending node (Figure 9).

And what of the comet itself, the cause of all this agony and ecstasy? Observations of Comet 55P/Tempel-Tuttle have been much rarer than observations of its debris. Yeomans *et al.* (1996) have recently recomputed its orbit, using the only known observations of the comet as it appeared in 1366, 1699, 1865-66 and 1965. As Yeomans *et al.* show in a revealing plot, on most of Tempel-Tuttle's returns it has been too faint to reach naked-eye visibility. In 1997 March, it was recovered at 22.5 magnitude, on its way to perihelion passage on 1998 February 28. At its minimum geocentric distance in 1998, it will be under tenth magnitude, and so easily within reach of moderate telescopes, but not the naked eye.

Whether or not the Leonid predictions for 1998 and 1999 are borne out will soon be known. In any event, meteors are an important case study of the growth in understanding of one class of solar system objects, a story that is unique and equally interesting for each class of astronomical bodies. Perhaps for few other classes of objects, however, have historic observations played such an important role in both discovery and elaboration, although we know from the work of Clark and Stephenson (1977), Stephenson (1978), and others that they do play a significant role in understanding such diverse phenomena as comets, eclipses, and supernovae. The role of historical data in meteor studies is thus only one example of how the history of astronomy demonstrates its usefulness to science. And the very existence of these data reminds us of how much astronomical phenomena have affected the civilizations of the past (Schaefer, 1992, 1994, 1997a, 1997b), perhaps more than we yet realize.

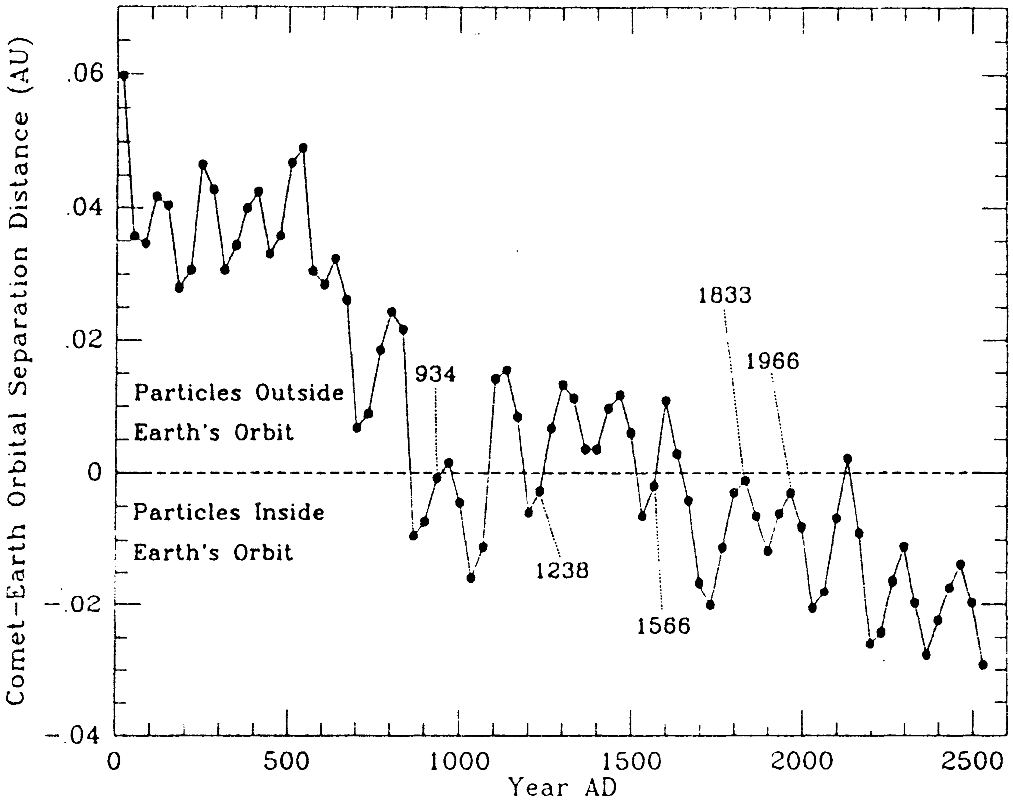

Figure 9. Minimum distances between Comet Tempel-Tuttle and Earth orbit at the time of the comet's passage through its descending node, from Yeomans *et al.* (1996). The plot indicates that after 1999 significant Leonids will be very rare. (From *Icarus* **124** (1996), 407-413, by permission of Academic Press, Inc. and D. K. Yeomans)

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