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METEOROID STREAMS

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The Evolution of Meteoroid Streams

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Abstract. The existence of meteoroid streams is indicated by the regular appearance of coherent meteor activity at specified times during the year. Since it is the interaction of the meteoroid with the atmosphere that is detected, the meteoroid has to be greater than about 100 micrometers in radius. Observation of these interactions gives information on individual meteoroids as well as collective phenomena. It is generally agreed that streams form through the ejection of dust particles from the surfaces of comets and asteroids at speeds considerably lower than the orbital speed. The subsequent motion of these particles is affected by gravitational perturbations from the planets and the effects of solar radiation forces. This review is intended to present an overview of the development of the subject and of our current state of knowledge.

1. Historical Overview

Numerous meteors, or shooting stars, can be seen on any clear night. Regular observation will show however that the occurrence of the meteors is not random and that many more meteors can be seen at certain times of the year, the first few days of January or the second week in August being good examples, than at other times. Such observations have been noted since antiquity and many accounts can be found of the regular appearances of well known showers. For example, the Perseids had long been referred to by Irish peasants as "the burning tears of St Lawrence" (Yeomans 1991). Hasegawa (1993) has produced a catalogue of ancient observations of meteor displays. In this, the first recorded appearance of the April Lyrids is as early as 687BC while the first Eta Aquarid is recorded on AD401. The appearance of a meteor implies that a meteoroid has entered the Earth's atmosphere and, except for the singular case where the orbit of the meteoroid lies in the ecliptic, this can only happen when the meteoroid is at one of the nodes of its orbit. The time of appearance of a meteor thus gives an accurate determination of the nodal position. From these historical records, it is clear that the longitude of the nodes evolves only slowly, something like a degree per century for the Leonids for example and less for the Perseids. The annual nature of meteor showers was first pointed out in a scientific discussion by Herrick (1838), while Newton (1863) appears to have been the first to comment that streams of small particles moving on orbits in the solar system would intersect the Earth's atmosphere on a sidereal cycle, as is observed. At about the same time, it had been recognized that gravitational perturbations would cause a change in the longitude of the nodes. The observed rate for the Leonids was used by Adams (1867) to show that a possible orbital period for the Leonid meteoroids was 33.25 years. Rather surprisingly, the notion that shooting stars were the visible trail of a small particle burning in the Earth's atmosphere is relatively recent. This must largely be due to the prevailing religious view until about the nineteenth century that the heavens were perfect and could not accommodate loose bits drifting about and to suggest such a thing was to invite ridicule if not worse. For example, a fall of meteorites was seen by at least 300 people near Agen in France on 1790 July 24, and meteorite fragments were exhibited, but this did not prevent the editor of the Journal des Sciences Utiles, Pierre Bertholon, from dismissing the whole affair as groundless and physically impossible. On 1807 December 14, a huge fireball was seen over a large section of New England and crashed to earth near Weston, Connecticut. Sillman, Professor of Chemistry and Kingsley, College Librarian, both of Yale College, collected many samples of this Weston meteorite but nevertheless President Thomas Jefferson is attributed with the probably apocryphal remark "it is easier to believe that two Yankee professors would lie than that stones would fall from heaven". However, at about the same time Chlandi (1794) had argued for a generic connection between meteors, fireballs and meteorites and for the extraterrestrial origin of all of them, while Benzenberg and Brandes (1800) had simultaneously observed 22 meteors from two locations a few kilometers apart and used the method of parallax to obtain their heights. This they found to have a mean value of 89km, a value that is essentially confirmed by modern measurements. This value is much too large to correspond to normal atmospheric phenomena and strongly pointed towards, even if it did not actually prove, an extra-terrestrial origin.

The timing of the spectacular Leonid meteor storm of 1833, seen over most of North America was very fortuitous because it came along just as the scientific world was beginning to take a serious interest in meteors. Olmstead (1834) and Twining (1834) established that the meteors of the Leonid storm appeared to emerge from a point within the constellation of Leo and that the meteors were moving on near-parallel tracks. In the same year, in a newspaper, Locke (1834) pointed out that the Perseids also had a fixed radiant or point of emergence. Thus, by the first half of the nineteenth century meteor astronomy had developed to the stage where it was understood that a meteor shower was caused by the Earth passing through a stream of small particles, these particles burning in the upper atmosphere to produce visible meteors. In terms of a general overview of what causes a meteor shower, this picture has hardly changed up to the present day, though quantitative values may have changed.

A question that immediately springs to mind is why do streams of particles, or meteoroids, moving on coherent similar orbits, exist within the solar system. Within 30 years of establishing their existence, astronomers had come up with the answer that is generally accepted today. Kirkwood (1861) had speculated that if comets released dust then this would indeed produce meteoroid streams but offered no observational evidence to back up the hypothesis. The first identification of a comet-meteor stream pair, the Perseids and comet 109P/ Swift-Tuttle, was by Schiaparelli (1867). Le Verrier (1867) accepted the period for the Leonids derived by Adams (1867) and pointed out that this was remarkably similar to the orbital period of the newly discovered comet 55P/ Tempel-Tuttle. Final confirmation of this viewpoint appeared to come from the

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observations of comet 3D/Biela. Prior to 1846, comet 3D/Biela was seen at a number of returns and appeared as a perfectly normal comet, with a period of around six and a half years. Observing conditions were not favorable for its predicted return in 1839 and unfortunately the comet was not observed. When it returned again in 1846, there were very clearly two comets present apparently moving on virtually identical orbits. By the next apparition in 1852 the separation of the two had increased but both were still clearly visible though much fainter than in 1846. Neither comet has been seen since that date. In 1872 the Earth passed through the node of the cometary orbit at a time close to when the comet, if it still existed, would have been there. A very strong meteor shower, variously called the Bielids or the Andromedids (as the radiant was close to the star Gamma Andromeda), was observed at that time. Strong Andromedid storms were subsequently observed in 1885, 1892 and 1899 (Lovell 1954). We should also note that Andromedids were also recorded in 1741, 1798, 1830 and 1838 (Hasegawa 1993). The generally accepted explanation of the observed sequence of events is that comet 3D/Biela had been ejecting meteoroids for some time prior to 1846 to form a meteoroid stream but that the disintegration of the nucleus, leaving no visible cometary remains, caused a localized enhancement in the number of meteoroids which in turn lead to the appearance of a strong meteor shower whenever these meteoroids could intersect the Earth's atmosphere. Babadzhanov et al. (1991) showed that the node of the orbit of 3D/Biela is now well outside the orbit of the Earth, so that Andromedid storms are no longer to be expected. The disintegration of 3D/Biela, together with a further spectacular display from the Leonid shower in 1866, were regarded as the final proof of the close association between comets and meteoroid streams.

Nineteenth Century astronomers were also aware of the importance of gravitational perturbations from the planets in terms of affecting the orbits of meteor streams. In particular, as mentioned already, they were well aware that planetary perturbations would cause an advancement of the nodes of the mean orbit. Thus in a period of about 70 years meteor science had advanced from a state where respectable scientists refused to believe in them as physical identities to a situation where a very clear understanding of their physical nature existed, an understanding which has not fundamentally changed to the present day. At this point, meteor studies came almost to a standstill for nearly a century, there being three independent reasons for this. The most important reason was probably a lack of understanding of the nature of the cometary nucleus. Without such an understanding, generating theories for the formation of streams was impossible and in consequence generating models designed to advance our understanding of their evolution was also difficult. Second, computational power was not available so that it was not possible to follow the orbital evolution of a swarm of particles under the effects of gravitational perturbations. Third, there was no realistic way of obtaining data on meteoroids other than through direct visual observations. As is often the case in science, these difficulties were overcome at about the same time, though it took a further quarter century before computers really became powerful enough to have a substantial impact on the subject.

2. The Modern Era.

The scientific breakthrough required in order to allow models of meteoroid streams to be constructed and compared with reality came when Whipple (1950) proposed the icy conglomerate model for cometary nuclei. According to this model a cometary nucleus consist of an icy matrix with dust grains embedded within it. As comets approach the Sun, the ices sublime and the gas outflow is initially capable of dragging grains with it. The important point about this idea is that it is possible to produce a quantitative model for grain ejection and, equally important, the resulting grain speed is moderately insensitive to the details of the model. In particular, the gas outflow speed will be of the order of the mean thermal velocity of water molecules at a temperature of a few hundred Kelvin, implying a maximum speed of the order of a kilometer per second. Grains will be accelerated through drag in this outflow and clearly cannot achieve a speed greater than the gas flow speed. The terminal speed achieved will depend on the mass-to-surface-area ratio. Hence in general one might expect that large particles have a small ejection speed while small particles are ejected at close to the gas outflow speed. However, such conclusions may not be true if large particles were an agglomeration of smaller ones since in this event the density of the larger particles may be less, thus partially compensating for the increase in radius. Such a possibility was suggested for example by Gustafson (1989a, 1990) and by Harris at al. (1995). A second obvious deduction is that there is a maximum particle size, above which gas drag is not capable of overcoming cometary gravity at the surface of the nucleus. This size turns out to be of order ten centimeters (see Williams 1992), though again this is increased somewhat if large particles are of low bulk density. Such a model was investigated initially by Whipple (1951), who produced a formula giving meteoroid ejection speeds that is widely used in modelling today (Fox et al. 1982, Jones & McIntosh 1986, Wu & Williams 1993). A number of authors have modified this Whipple formula (Hughes 1977, Gustafson 1989b, Williams 1992) but the end result in terms of a real change in velocity is small. At the other end of the size scale, radiation pressure will cause very small particles to escape from the solar system. Kresak (1974) showed that it was not necessary for radiation pressure to exceed solar gravity for this to happen, all that is necessary is for the energy to become positive and this typically occurs when the ratio of radiation pressure to gravity exceeds about 0.1. Hence particles smaller than about ten microns, ejected from a cometary nucleus, will be lost from the solar system and meteoroid streams formed in this way will be initially composed of meteoroids within the range of ten microns to ten centimeters.

Of course, it does not follow that all meteoroids within meteoroid streams fall within this size range, larger grains could be present if the formation process was different from that described. One obvious way in which larger meteoroids can be introduced into a stream is through a partial or complete disintegration of the parent nucleus as was the case for 3D/Biela for example. An other possibility is that some meteoroid streams may have asteroidal parents (Hoffmeister 1948, Plavec, 1956, Sekanina 1973, Stohl & Porubcan, 1993, Steel 1995). In this event, ejection is the consequence of collision and so the upper limit to the size does not apply. It is harder to overcome the lower limit restriction, since, as radiation forces become more important, they are more likely to remove rather than add small meteoroids.

With an understanding of the ejection mechanism and a formula for the speed, vectorial addition gives the heliocentric velocity of the meteoroid and hence its initial orbit. The problem is then reduced to a dynamical one of following the evolution of an orbit under the effect of perturbations. The ejection speed is generally considered to be substantially smaller than the orbital speed of the cometary nucleus. Consequently, the orbit of the meteoroid will only differ slightly from that of the parent and this is the main reason why the concept of a meteoroid stream is meaningful. However, with a small change in energy (and thus semi-major axis) the change in aphelion distance is generally much greater than the change in perihelion distance. Consequently, streams may be obvious when encountered near perihelion (as is generally the case on Earth) but far less obvious when encountered close to aphelion.

Orbital calculations under perturbations have been carried out with great success on comets in the eighteenth and nineteenth centuries and indeed many of the numerical integration methods, very familiar to us these days, are associated with names such as Newton, Gauss, Adams and Cowell. However, little of this computational work was applied to meteoroid streams, presumably in recognition of the fact that the calculations were actually carried out by hand and, while this was feasible for a small number of important comets, it was not practical to compute the orbits of individual meteoroids. By the second half of the twentieth century, secular perturbation methods were becoming popular. In such methods, changes are averaged over one orbit so that only secular variations remain. Many methods were developed which work well for near- circular orbits, but Brouwer (1947) developed a method which also worked for highly eccentric orbits. This method was used by Whipple & Hamid (1950) to show that 4700 years ago, the orbits of comet 2P/Encke and the Taurid stream were very similar and they suggested an association, between the comet and the stream, an association that is now generally accepted (Jones 1986, Steel et al. 1991). Also using secular perturbation methods, Plavec (1950) showed that the orbit of the Geminids was evolving very rapidly so that the Geminid shower seen on Earth can only have been visible for a few hundred years at most during the current intersection epoch. This result was confirmed by later more detailed calculations (Hunt et al. 1985, Jones & Hawkes 1986, Gustafson 1989a, Williams & Wu 1993). A very efficient and popular secular perturbation method is the Gauss-Halphen-Goryachev method (see Hagihara 1972 for a description of the actual method). This method was extensively used in the 1980's by Babadzhanov & Obrubov (eg 1980, 1983) to investigate the evolution of a number of streams. The main disadvantages of the secular methods are that in averaging over an orbit, the effects of close encounters can be lost while the averaging also removes all dependence on the initial mean anomaly so that dispersal of the stream due to slightly different perturbations are also lost. The advantage is clear: a huge saving in computation time.

The emergence of the electronic computer and the rapid increase in computational capability completely changed the study of meteoroid stream evolution, allowing for the first time the motion of a number of test meteoroids to be followed over a reasonable period of time. The first such investigation was probably by Hamid & Youssef (1963) who integrated the orbits of six actual Quadrantid meteors and concluded that drastic changes in their orbits were taking place on timescales of a thousand years. A few years later. Levin et al. (1972) demonstrated. again through numerical integration, that one general effect of Jupiter on meteoroid streams was to increase their widths and, in consequence, reduce their spatial density, over time. In 1979, Williams et al. (1979) also studied the Quadrantid stream, but used ten hypothetical meteoroids placed on the mean orbit and uniformly distributed in eccentric anomaly in an attempt to analyze differences in their evolution. Such differences could not be found using secular perturbation methods and illustrates the main advantage of using a set of meteoroids. The conclusions of this investigation generally agreed with those of Hamid & Youssef. The number of test meteoroids was increased by an order of magnitude by Hughes et al. (1981) who used 210 to investigate the nodal regression rate of the Quadrantids. This investigation showed that meteoroids close to a mean orbit resonance with Jupiter behaved in very erratic ways, though Hughes et al. did not use the word "chaotic" to describe the motion. In the same year Froeschle & Scholl (1981), using a different integration method, found evidence for chaotic motion amongst the Quadrantid meteoroids and peculiar motion was also found close to the 2:1 resonance with Jupiter by Froeschle & Scholl (1986). Wu & Williams (1992) identified 122 Quadrantid meteoroids within the IAU Meteor Data Center records at Lund and found evidence for chaotic behavior in fifteen of them.

In an investigation of the Geminid stream, Fox et al. (1982), increased the number of test meteoroids to 1000, though the integration was only performed over a short time interval of 150 years. By 1983, computer technology had advanced to the state when Fox et al. (1983) was able to follow the motion of 500 000 test meteoroids over 500 years. With such numbers it was possible to obtain two-dimensional models of the cross section of the stream that bore some resemblance to reality. By the mid-eighties, the use of direct numerical integration had become very widespread, examples being Jones (1985), Hunt et al. (1985), Jones & McIntosh (1986), Gustafson (1989a), Babadzhanov et al. (1991), Jones & Jones (1992), Asher et al. (1993), Brown and Jones (1993), Williams & Wu (1993, 1994), Wu & Williams (1995). The general availability of computing power suggests that this area will continue to be highly productive for some time.

The third development that was mentioned earlier, namely the ability to observe meteors by means other than naked eye or binoculars, started in the thirties with the Havard photographic program and the use of rocking mirrors to obtain photographs in Arizona. This development accelerated after the second World War with the use of cameras with a precisely-timed occulting device to provide accurate velocity data for any meteor photographed from at least two locations. At least three major networks came into existence at about this time. The Prairie Network in central USA ran from 1964 to 1974, the MORP project in western Canada operated from 1971 to 1985 and the European Network in the Czech Republic, the Slovak Republic and Germany started in 1964 and is the only net that survives. Many orbits were obtained by these networks and thankfully many of these are now safely archived in the IAU Meteor Data Center at Lund. However, a significant fraction of the data obtained remain outside the archives at Lund and it is important that someone undertakes the task of retrieving these data before they are lost. Many searches, far too numerous to mention here, of the data in the IAU Meteor Data Center have been carried out, sometimes in the hope of finding new streams, but more often, and more usefully, to improve the orbital elements of well-known streams. This is a task which, rather surprisingly, can often be very rewarding. For example, the orbit for the well known Eta Aquarid shower given by Cook (1973), and generally used by the community, was based on the orbit of a just one meteor Lindblad (1990), using orbits identified from the Lund catalogue, increased the number of orbits used by an order of magnitude and in consequence obtained a different and much more reliable mean orbit for the Eta Aquarids

An improvement of the photographic multi-station networks, at least in that visible meteors are recorded, is the use of low light level television methods. Active work known to the author in this field is underway in Canada, The Czech Republic, Japan, the Netherlands, Tajikstan and the USA. A review of this topic was given by Hawkes (1993) and a good example of what can be achieved using camcorders are the records of the Peekskill fireball over the eastern USA in October 1992.

Following the development of radar and the radio wave band generally during the 1939-45 war, its value as a tool to investigate meteor trails was realized. Many radar systems were developed and, thankfully, a significant number are still operating. The systems, being essentially automatic, have the capacity to produce vast amounts of data with, for example, the AMOR system in New Zealand recording several hundred thousand orbits per year (Baggaley et al. 1994).

With the vast increase in the number of orbits available, it became necessary to produce a criterion for quantifying similarities between orbits. One criterion by Southworth & Hawkins (1963), modified by Drummond (1981a), is the so called D-criterion. Another problem is to differentiate between a stream and the sporadic background. This problem is compounded by the fact that asteroids, particularly those in the Apollo-Amor group, are also capable of producing meteoroid streams, as shown by Olsson-Steel (1988) in contradiction to an earlier result by Drummond (1981b). This problem was recently reviewed by Steel (1995).

Some further increase in our observational capabilities came from the space age, where space vehicles can now, in principle at least, observe meteoroids in situ as well as observe at wavebands not usable from the ground. A good example of the latter was the detection of dust-bands trailing behind some comets (see Sykes & Walker 1992), while a review of the former aspect is given by Grun (1993). However, it should be remembered that the dust grains detected by most space vehicles are smaller than the lower limit in size for meteoroids that we mentioned earlier. One problem which arises when using space vehicles to study meteor streams is that the actual Cartesian spacing between meteoroids on similar orbits increases significantly as the meteoroids move away from perihelion (see Williams et al, 1993 Figure 2 for an illustration of this) and many space experiments are sampling well away from perihelion.

Thus, at the present time, data are readily available on the orbits of a large number of meteoroids belonging to streams, computer search techniques exist for finding streams from such catalogues and computer time is generally available to allow the numerical integration of the equations of motion, including radiation forces, of thousands of test meteoroids to be performed thus allowing the stream models to be reasonable approximations of actual streams. In general, the agreement between observations and simulations are such that one can safely conclude that the overall picture so far presented is close to the truth.

3. The Future

Though the general picture is one of agreement between theory and observations, there are some areas that need closer investigation and possibly some new insight. The most obvious is the observed spread in the semi-major axes of stream meteoroids. Numerous investigations have shown that most of this spread cannot come from the effects of perturbation, radiation forces and so forth for the simple reason that when averaged over a reasonable time period, all meteoroids suffer essentially the same perturbations. Therefore, some of the spread must be caused by the initial ejection process and speeds in excess of those given by the Whipple (1951) formula are called for. One could increase the ejection speed at the surface of the nucleus, through increasing the gas outflow speed or drag coupling of meteoroids to the gas, as suggested by Gustafson (1989a), Harris et al. (1995). An alternative suggestion (Steel 1994) is that meteoroids are accelerated through the cometary coma through outgassing of volatiles from the meteoroids themselves. This is an area ripe for further investigation.

As mentioned already, the spectacular bursts of the Leonid shower were responsible for the initial interest in meteor showers. The Leonids are not alone in producing such outbursts, the Draconids (Lindblad 1987) and the April Lyrids (Lindblad & Porubcan 1992) are also well known for producing outbursts. Indeed recently the Perseids also produced an outburst, (Rendtel 1993) which would have been classified as spectacular had it occurred in the Draconids or the Lyrids. The interesting thing about these outbursts is that they all appear to have different characteristics. In both the Perseids and the Leonids, the outbursts are firmly correlated to the time around the return of the parent comet. This cannot be so in the case of the Lyrids, (Arter & Williams 1995) while the Draconids appear to produce meteoroids at locations relative to the comet that are counter intuitive (Wu & Williams 1995). This is also an area ripe for investigation.

A third area that has not received much attention in the past is that of the loss of meteoroids from streams and the contribution this makes both to the sporadic background and to the general interplanetary dust population. The main reason for the lack of attention is probably the difficulty of making progress because in order to understand the loss through collision, some understanding of the structure of meteoroids is called for. When estimates for densities of individual meteoroids (Babadzhanov, 1993) varies by a factor of ten, one might think that this understanding has perhaps some way to progress. Nevertheless, with progress in the analysis of interplanetary dust and an increased understanding of the interaction between small fragile particles and the atmosphere, a solution to the structure problem is also in sight and I believe that we are close to the situation where the study of meteor showers will be regarded as a means of probing the structure of their parents rather than as a phenomenon to be studied in its own right (see Adolfsson & Gustafson, 1996).

References

Adams, J. C. 1867, MNRAS, 27, 247

Adolfsson, L. & Gustafson, B.A.S. 1996, this volume

Arter, T. R. & Williams, I.P. 1995, MNRAS, 277, 1087

Asher, D.J., Clube, S.V.M.and Steel, D.I.,1993, MNRAS, 264, 93

Babadzhanov, B.P. 1993, in Meteoroids and their parent bodies. Eds Stohl, J. & Williams, I.P., Slovak Academy of Sciences, Bratislava, 295.

Babadzhanov, P. B. & Obrubov, Y V. 1980, Solid Particles in the Solar System, Eds.Halliday, I. & McIntosh, B.A, Reidel , Dordrecht, 157

Babadzhanov, P. B. & Obrubov, Y.V. 1983, Highlights in Astronomy vol 6, Ed West, R.M., Reidel , Dordrecht, 411

Babadzhanov, B.P., Wu, Z., Williams, I.P. & Hughes, D.W. 1991, MNRAS, 253, 69.

Baggaley, W.J., Bennett, R. G. T.,Steel, D. I.and Taylor, A.D. 1994, QJRAS, 35, 293

Benzenberg, J.F. & Brandes, H.W 1800, Annalen der Phys, 6, 224

Brouwer, D. 1947, AJ., 52, 190

Brown, P. & Jones, J. 1993, in Meteoroids and their parent bodies. Eds Stohl, J. & Williams, I.P., Slovak Academy of Sciences, Bratislava, 41

Chlandi, E. F. F., 1794, Über den ursprung der von Pallas gefunden und anderen ahnlichen. J.F Hartknoch, Riga

Cook, A.F. 1973, Evolutionary and physical properties of Meteoroids, NASA SP-319, Washington DC, 183

Drummond, J.D. 1981a, Icarus, 45, 545.

Drummond, J.D. 1981b, Icarus, 47, 500

Fox, K., Williams, I.P & Hughes, D.W. 1982, MNRAS, 200, 313

Fox, K., Williams, I.P. & Hughes, D.W 1983, MNRAS, 205, 1155

Froeschle, C. & Scholl, H., 1981 A&A, 93, 62.

Froeschle, C. & Scholl, H. 1986 in Asteroids Comets Meteors II, Eds C.-I. Lagerkvist, B. A. Lindblad, H. Lundstedt & H. Rickman, Uppsala University Reprocentralen. 555

Grun, E., 1993, in Meteoroids and their parent bodies. Eds Stohl, J. & Williams, I.P., Slovak Academy of Sciences, Bratislava, 349

Gustafson, B.A.S. 1989a, ApJ, 337, 945

Gustafson, B.A.S. 1989b, A&A, 225, 533.

Gustafson, B.A.S. 1990, in Asteroids, Comets, Meteors III, Eds C.-I. Lagerkvist, H. Rickman, B.A. Lindblad & M. Lindgren, Uppsala Universitet Reprocentralen, 523

Hagihara, Y., 1972, Celestial Mechanics, vol 2, MIT Press, London.

Hamid, S.E. & Youssef, M.N. 1963, Smithson. Cont. Astrophys.,7,309

Harris, N. W. , Yau, K.K. & Hughes, D.W 1995, MNRAS, 273, 999

Hasegawa. I. 1993, in Meteoroids and their parent bodies. Eds Stohl, J. & Williams, I.P., Slovak Academy of Sciences, Bratislava, 209

Hawkes, R.L., 1993, in Meteoroids and their parent bodies. Eds Stohl, J. & Williams, I.P., Slovak Academy of Sciences. Bratislava, 227

Herrick, E. C., 1838, American Jl. Science, 33, 176

Hoffmeister, C., 1948. Meteorstrome. Johan Ambrosius Barth, Leipzig,

Hughes, D. W. 1977, Space Res., 17, 565

Hughes, D. W., Williams, I.P. & Fox, K., 1981, MNRAS, 195, 625.

Hunt, J., Williams, I.P & Fox, K., 1985, MNRAS, 217, 533.

Jones, J., 1985, MNRAS, 217, 523

Jones, J., 1986, MNRAS, 221, 257

Jones, J. & Jones, W. 1992, in Asteroids. Comets, Meteors 1991, Eds Harris, A.W. & Bowell, E., Lunar & Planetary Institute Press, Houston, 269

Jones, J & Hawkes, R. 1986, MNRAS, 223. 479.

Jones. J. & McIntosh, B. A. 1986, Exploration of Comet Halley, ESA SP-250, Paris, 233

Kresak, L. 1974, Bull. astr. Inst. Czechoslov., 13 ,176

Kirkwood, D 1861. Danville Quarterly Review, December 1861

Le Verrier, U. J. J 1867, Comptes Rendus, 64, 94

Levin, B. Y., Simonenko, A. N. & Sherbaum, L. M., 1972, in The Motion, Evolution of Orbits and Origin of Comets. Eds Chebotarev, G. A. et al., Reidel, Dordrecht

Lindblad. B.A. 1987, A&A. 187, 928

Lindblad, B.A. 1990, in Asteroids, Comets, Meteors III, Eds C.-I. Lagerkvist, H. Rickman, B.A. Lindblad & M. Lindgren, Uppsala Universitet Reprocentralen, 551

Lindblad, B.A. & Porubcan. V 1992. in Asteroids, Comets, Meteors 1991, Eds Harris, A.W & Bowell. E., Lunar & Planetary Institute Press, Houston, 367

Locke, J. 1834, Cincinati Daily Gazette, 1834 August 11 and 12

Lovell, A.C.B. 1954, Meteor Astronomy, Oxford University Press

Newton. H. A. 1863. American Jl. of Sci. and Arts, 36, 145

Olmstead. D., 1834, American Jl. of Science, 29, 376

Olsson-Steel. D. 1988, Icarus. 75, 64

Plavec, M. 1950,. Nature, 165. 362

Plavec. M. 1956. Meteor Streams, Czechoslov Acad.of Sciences, Prague 367

Rendtel, J. 1993, WGN, 21, 235

Schiaparelli. G V. 1867, Astronomische Nachrichten, 68, 331.

Sekanina, Z. 1973. Icarus, 18, 253

Southworth. R. B. & Hawkins. G.S. 1963. Smithson. Cont. Astrophys., 7. 261

Steel, D.I. 1994, in Asteroids, Comets. Meteors 1993. Eds A. Milani. M. Di Martino & A. Cellino. Kluwer. Dordrecht. 111.

Steel, D.I. 1995. Earth. Moon, and Planets, 68,13

Steel, D., Asher, D.J. & Clube, S.V.M. 1991, MNRAS, 251, 632

Stohl, J.and Porubcan, V. 1993, in Meteoroids and their parent bodies. Eds Stohl, J. & Williams, I.P., Slovak Academy of Sciences, Bratislava, 41

Sykes, M.V. & Walker, R.G. 1992, Icarus, 95, 180

Twining, A. C., 1834, American Jl. Sciences, 26, 320.

Whipple, F. L. 1950, ApJ., 111, 375

Whipple, F. L. 1951, ApJ., 113, 464

Whipple, F. L. & Hamid S.E.D. 1950, Sky & Telescope, 9, 248

Williams, I.P. 1992, in Chaos, Resonance and Collective Phenomena in the Solar System, Ed Ferras-Mello,S., Kluwer, Dordrecht 299

Williams, I.P., Hughes, D.W., McBride, N. & Wu, Z. 1993, MNRAS, 260, 43

Williams, I. P., Murray, C. D. & Hughes, D. W 1979, MNRAS, 189, 483.

Williams, I.P. & Wu, Z. 1993, MNRAS, 262, 231

Williams, I.P. & Wu, Z. 1994, MNRAS, 269, 524

Wu, Z. & Williams, I.P. 1992, MNRAS, 259, 617

Wu, Z. & Williams, I.P. 1993, MNRAS, 264, 980

Wu, Z. & Williams, I.P. 1995, Planet. Space Sci., 43, 723

Yeomans, D. K. 1991, Comets: a Chronological History of Observations, Science, Myth and Folklore, J. Wiley and Son, New York

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