Dynamical Evolution of Meteoroid Streams, Developments Over the Last 30 Years

I. P. Williams

Abstract As soon as reliable methods for observationally determining the heliocentric orbits of meteoroids and hence the mean orbit of a meteoroid stream in the 1950s and 60s, astronomers strived to investigate the evolution of the orbit under the effects of gravitational perturbations from the planets. At first, the limitations in the capabilities of computers, both in terms of speed and memory, placed severe restrictions on what was possible to do. As a consequence, secular perturbation methods, where the perturbations are averaged over one orbit became the norm. The most popular of these is the Halphen-Goryachev method which was used extensively until the early 1980s. The main disadvantage of these methods lies in the fact that close encounter can be missed, however they remain useful for performing very long-term integrations.

Direct integration methods determine the effects of the perturbing forces at many points on an orbit. This give a better picture of the orbital evolution of an individual meteoroid, but many meteoroids have to be integrated in order to obtain a realistic picture of the evolution of a meteoroid stream. The notion of generating a family of hypothetical meteoroids to represent a stream and directly integrate the motion of each was probably first used by Williams Murray & Hughes (1979), to investigate the Quadrantids. Because of computing limitations, only 10 test meteoroids were used. Only two years later, Hughes et. al. (1981) had increased the number of particles 20-fold to 200 while after a further year, Fox Williams and Hughes used 500 000 test meteoroids to model the Geminid stream. With such a number of meteoroids it was possible for the first time to produce a realistic cross-section of the stream on the ecliptic.

From that point on there has been a continued increase in the number of meteoroids, the length of time over which integration is carried out and the frequency with which results can be plotted so that it is now possible to produce moving images of the stream. As a consequence, over recent years, emphasis has moved to considering stream formation and the role fragmentation plays in this.

Keywords meteors · numerical integration · modeling

1 Introduction

Understanding the basic physics involved in meteoroid stream evolution is relatively easy. First, some model for the ejection of material from the parent body, that is time (location), speed and direction is needed. From this the initial orbit of each meteoroid can be calculated. Some means of calculating the effects of gravity from the Sun and Planets on the orbits of these meteoroids is then required which should also incorporate the effects of Solar Radiation (Pressure and the Poynting-Robertson effect). Hence the orbit of each meteoroid can be calculated at any desired time after the initial formation. Finally if the meteoroid position coincides with that of the Earth, there is a need to understand the

I. P. Williams (✉)
Queen Mary University of London, Mile End Rd, E1 4NS, UK. E-mail: i.p.williams@qmul.ac.uk

interaction between the meteoroids and the atmosphere so that the observed meteor shower can be tied in with the meteoroid stream.

Walker (1843) drew attention to the similarity, in terms of eccentricity, between meteor and comet orbits, but it was left to Kirkwood (1861) to propose that shower meteors were debris of ancient comets. At that time, the standard model for comets was essentially the flying sandbank model, so that initially the velocity of the meteoroids were essentially the same as that of the comet, there was no need for an ejection model. LeVerrier (1867) correctly pointed out that, given sufficient time, planetary perturbations would spread the meteoroids all around the orbits. Newton (1864 a, b) showed that the node of the Leonid orbits advanced relative to a fixed point in space at 52.4 arc seconds per year and Adams (1867) showed that a 33.25 year period was the only period that was consistent with the observed nodal advancement. Thus, early workers were incorporating the principles laid down above into their thoughts but computers were human assistants rather than machines and of necessity rather slow.

2 New Techniques and Thoughts

Nagaoka (1929) had suggested that meteors could affect the propagation of radio waves, a suggestion also made by Skellet (1931, 1932), but little was done. Hey realized that radar could be used as a tool to investigate meteors and at the end of the war ensured that military radar equipment became available for civil use allowing astronomers to start meteor work. There was a strong storm of Draconid meteors in 1946. This resulted in several papers being published on radar observations of the Draconids (Clegg et. al. 1947, Hey et. al. 1947, Lovell et. al. 1947). Radar can detect smaller meteoroids (down to sub-millimetre size) and so detected many more meteors. Radar also had the advantage of working in the day as well as by night, thus doubling the coverage and discovering many new streams (Ellyett 1949) and orbits of thousands of meteors were obtained.

Whipple (1950) proposed a new model for a comet, replacing the flying sandbank model. According to this model, a comet had an icy nucleus with dust grains embedded within it, the dirty snowball model. As a comet approaches the sun, solar heating causes the ices to sublimate and the resulting gas outflow carries away small dust grains with it, the larger ones becoming meteoroids and the very small ones forming the dust tail. Whipple, (1951) modelled this and produced an expression for the ejection velocity, V of the meteoroids relative to the cometary nucleus at a heliocentric distance r as

$$V^2 = 4.3 \times 10^5 R_c \left(\frac{1}{b\sigma r^{2.25}} - 0.013 R_c\right)$$

where σ is the bulk density of the meteoroid and r the heliocentric distance in astronomical units. R_c is the nucleus radius in kilometers and all other quantities are in cgs units. Others (e.g. Gustafson 1989, Crifo 1995, Ma et al, 2002), have modified this model, but the general result is the same, namely that the outflow speed of the meteoroids is much less than the orbital speed of the comet. Thus there is little change in the specific energy and momentum of these meteoroids and so they move on similar orbits to that of the comet, in other words, they form a stream. If the ejection velocity is known relative to the nucleus, then the heliocentric velocity can be calculated and from this, the initial orbit. The mathematics involved in this and the relevant equations are given in detail in Williams (2002).

Initially, computing capabilities were too limited to allow direct integration of a significant set of meteoroids and so secular perturbations were commonly used, generally based on an algorithm by

Brouwer (1947) that could be applied to orbits with high eccentricity, all previous methods relied on using a series expansion that was valid only for low values of *e*. This mathematical development allowed Whipple & Hamid (1950) to follow the evolution of the mean Taurid stream over an interval of 4700 years. Secular perturbation methods were the prime method of investigation and became quite sophisticated, the most popular being the Halphen-Goryachev method described in Hagihara (1972). This was used by Galibina & Terentjeva (1980) to determine the effect of gravitational perturbations on the stability of a number of meteoroid streams over a time interval of tens of thousands of years. Babadzhanov & Obrubov (1980, 1983) also used the Halphen-Goryachev method to investigate the evolution of both the Geminid and the Quadrantid streams. The major draw-back of any secular perturbation method is that it deals with the evolution of orbits rather than determining the position of individual meteoroids (that is, no account is taken of true anomaly). Hence, the method may show that the orbits of meteoroids intersect the Earth's orbit, but unless meteoroids are present at that location at that time, no meteors will be seen. This consideration is particularly important for showers like the Leonids as was discussed by Wu & Williams (1996), Asher et. al. (1999).

3 Direct Integration Methods

Direct integration methods integrate the path of each individual meteoroid and this was done by Hamid & Youssef (1963) for the six meteoroids then known to belong to the Quadrantid stream. The difficulty is that as there are at least 10^{16} meteoroids in a typical stream so that the six observed meteors are almost certainly not a representative sample of the whole stream. However, a smaller sample has to be taken to represent the stream, in reality a set of test particles have to be generated to represent the stream. This was done 30 years ago by Williams et. al. (1979), who represented the Quadrantid stream by 10 test particles, spread in uniformly in true anomaly around the orbit and integrated over an interval of 200 years using the self adjusting step-length Runge-Kutta 4th order method.

Four years later, Fox et al. (1983) were using 500 000 meteoroids and were able to produce a theoretical cross section on the ecliptic for the Geminid stream which gives vital information about the properties of the resulting shower. Jones (1985) used similar methods to produce a stream cross section. In four years computer technology had advanced from allowing only a handful of meteoroids to be integrated to the situation where numbers to be used did not present a problem.

By the mid eighties, complex dynamical evolution was being investigated, Froeschlé and Scholl (1986), Wu & Williams (1992) were showing that the Quadrantid stream, experiencing close encounters with Jupiter, was behaving chaotically. A new peak in the activity profile of the Perseids also caused interest with models being generated by Wu & Williams (1993) for example. Williams & Wu (1994) were able to show how the cross-section of the Perseid shower should vary from year to year. Babadzhanov et al. (1991) looked at the possibility that the break-up of comet 3D/Biela was caused when it passed through the most heavily populated part of the Leonid stream.

By now calculating from models the likely cross-section at any given time has become routine (Jenniskens & Vaubaillon 2008, 2010).

4 A Problem Emerges

The Quadrantid shower is a prolific and regular shower seen at Northern latitudes around the beginning of January. It is arguably the only major meteor shower that does not have a body that is generally accepted as being its parent. Part of the problem of identifying the parent undoubtedly lies in the fact that orbits in this region of the Solar System evolve very rapidly so that claims can be made based on a similarity of orbits at some epoch in the past. Equally, a similarity of orbits at the current time alone is not a proof of parenthood. The history of the Quadrantid meteoroid stream, including a discussion of most of the suggested parent bodies can be found in Williams & Collander-Brown (1998).

One of the suggestions for the parent of the Quadrantids is comet C/1490 Y1 (Hasegawa, 1979), the claim being based on orbital similarity around 1490 AD. In the Quadrantid shower there is both a strong narrow peak and a broad background showing the existence of both an old stream and a new one (Jenniskens et. al. 1997). There is an asteroid, 2003 EH1 with an orbit that is currently almost identical to the mean orbit of the Quadrantids and it has been argued that this asteroid may be a surviving remnant of the comet of 1491, following its catastrophic break-up (Jenniskens 2004, Williams et. al. 2004). We now know that comet break-up is fairly common and so one might expect meteor streams with such an origin to be also common. The Taurid complex is also generally considered to consist of comet 2P/ Encke, a significant number of asteroids and of course the Taurid meteor streams, suggesting a past fragmentation (Babadzhanov et. al. 2008, Napier 2010).

5 Conclusions

In the last 30 years, the field appears to have gone full circle. In the beginning it was generally agreed that we knew how meteor streams formed, but were struggling to follow the effects of perturbations on the orbits. Now we are confident that we can follow the evolution of any given set of orbits but are struggling to model the stream formation process when partial or total disintegration takes place.

References

Adams J.C. On the orbit of the November meteors, *MNRAS*, 27:247-252, 1867

Asher D.J. Bailey M. E. Emel'Yanenko V.V. Resonant meteors from comet Tempel-Tuttle in 1333: the cause of the unexpected Leonid outburst in 1998, *MNRAS*, 304:L53-57, 1999

Babadzhanov P.B. Obrubov Y.Y. Evolution of orbits and intersection conditions with the Earth of Geminid and Quadrantid meteor streams, in *Solid particles in the Solar System*, Eds Halliday I. McIntosh B.A., D.Reidel, Dordrecht, 157-162, 1980

Babadzhanov P.B. Obrubov Y.Y. Some features of evolution of meteor streams, in *Highlights in Astronomy*, Ed West R.M., D. Reidel Dordrecht, 411-419, 1983

Babadzhanov P.B. Williams I.P. Kokhirova G. I. Near-Earth Objects in the Taurid complex, *MNRAS*, 386:1436-1442 2008

Babadzhanov P.B. Wu Z. Williams I.P. Hughes D.W. The Leonids, Comet Biela and Biela's associated Meteoroid Stream, *MNRAS* 253:69-74, 1991

Brouwer D. Secular variations of the elements of Enckes comet, *AJ*, 52:190-198, 1947

Clegg J.A. Hughes V.A. Lovell A.C.B. The Daylight Meteor Streams of 1947 May-August, *MNRAS*, 107:369-378, 1947

Crifo J.F. A general physiochemical model of the inner coma of active comets I. Implications of spatially distributed gas and dust production, *Ap.J* 445:470-488, 1995

Ellyett C.D. The daytime meteor streams of 1949: measurement of velocities, *MNRAS*, 109:359-364, 1949

Froeschlé C. Scholl H. Gravitational splitting of Quadrantid-like meteor streams in resonance with Jupiter, *A&A*, 158:259-265, 1986

Fox K. Williams I.P. Hughes D.W. The rate profile of the Geminid meteor stream, *MNRAS*, 205:1155-1169, 1983

Galibina I. V. Terentjeva A. K. Evolution of meteors over milenia in *Solid particles in the Solar System*, Eds Halliday I. McIntosh B.A., D.Reidel, Dordrecht, 145-148, 1980

Gustafson B.A.S. Comet ejection and dynamics of non-spherical dust particles and meteoroids, *Ap.J*, 337:945-949, 1989

Hagihara Y. *Celestial Mechanics*, MIT Cambridge Mass 1972

Hamid S. E. Youssef M. N. A short note on the origin and age of the Quadrantids *Smithson. Contr. Astrophys*. 7:309-311, 1963

Hasegawa I. Historical records of meteor showers, in *Meteors and their parent bodies*, Eds Stohl J. Williams I.P., Astronomical Institute, Slovak Academy of Sciences, Bratislava, 209-223, 1983

Hey J.S. Parsons S.J. Stewart G.S. Radio Observations of the Giacobinid Meteor shower, *MNRAS*, 197:176-183, 1947

Hughes D.W. Williams I.P. Fox K. The mass segregation and nodal retrogression of the Quadrantid meteor stream, *MNRAS*, 195:625-637, 1981

Jenniskens P. 2003 EH1 Is the Quadrantid Shower Parent Comet, *AJ*, 127:3018-3022, 2004

Jenniskens P. Vaubailllon J. Minor Planet 2008 ED69 and the Kappa Cygnid Meteor Shower, *AJ*, 136:725-730, 2008

Jenniskens P. Vaubaillion J Minor Planet 2002EX12 (169P/Neat) and the Alpha Capricornid shower, *AJ*, 139:1822-1830, 2010

Jenniskens P. Betlen H. De linge M. Langbroek M. Van Vliet M. Meteor stream activity V. The Quadrantids, a very young stream, *A&A*, 327:1242-1252, 1997

Jones J The structure of the Geminid Meteor Stream: I the effect of planetary perturbations, *MNRAS*, 217:523-532, 1985

Kirkwood D. Cometary astronomy, *Danville Quarterly Review*, 1:614-618, 1861

LeVerrier U.J.J. Sur les etoiles filantes de 13 Novembre et du 10 Aut, *Comptes rendus*, 64:94-99, 1867

Lovell A.C.B.Banwell C.J. Clegg J.A. Radio Echo observations of the Giacobinid Meteors, *MNRAS*, 107:164-175, 1947

Ma Y. Williams I.P. Chen W. On the ejection velocity of meteoroids from comets, *MNRAS*, 337:1081-1086, 2002,

Nagaoka, H. Possibility of the radio Transmission being disturbed by Meteoric showers, *Proc. Imp. Acad. Tokyo*, 5:233-236, 1929

Napier W.M. Palaeolithic extinctions and the Taurid Complex, *MNRAS*, 405:1901-1906, 2010

Newton H.A. The original accounts of the displays in former times of the November star-shower, together with a determination of the length of its cycle, its annual period, and the probable orbit of the group of bodies around the Sun, *American Jl of Science and Arts series 2*, 37:377-389, 1864a

Newton H.A. The original accounts of the displays in former times of the November star-shower, together with a determination of the length of its cycle, its annual period, and the probable orbit of the group of bodies around the Sun, *American Jl of Science and Arts series 2*, 38:53-61, 1864b

Skellett A.M. The effect of Meteors on Radio transmission through the Kennelly-Heavyside Layer, *Phys. Rev*., 37:1668, 1931

Skellett A.M. The ionizing effect of Meteors in relation to Radio Propagation, *Proc. Inst. Radio Eng.*, 20:1933-1941, 1932

Williams I.P. Wu Z. The Quadrantid meteoroid stream and comet 1491 I, *MNRAS*, 264:659-664, 1993

Walker S. E. Rearches concerning the Periodic Meteors of August and November, *Trans. American Phil. Soc.*, 8:87-140, 1843

Whipple F.L. A comet model I; The acceleration of comet Encke, *Ap.J*, 111:375-394, 1950

Whipple F.L. A comet model II: Physical relations for comets and meteors, *Ap.J*, 113:464-474, 1951

Whipple F.L. Hamid S.E. On the origin of the Taurid meteors, *AJ*, 55:185-186, 1950

Williams I.P., 2002, The evolution of meteoroid streams, in *Meteors in the Earth's Atmosphere*, Eds Murad E Williams I.P., CUP Cambridge, 13-32

Williams, I. P. Collander-Brown, S. J. The parent of the Quadrantid meteoroid stream, *MNRAS*, 294:127-138, 1998

Williams I.P. Murray C.D. Hughes D.W. The long-term orbital evolution of the Quadrantid stream, *MNRAS*, 189:483-492, 1979

Williams I.P. Ryabova G.O. Baturin A.P. Chernitsov A.M. The parent of the Quadrantid meteoroid stream and asteroid 2003 EH1, *MNRAS*, 355:1171-1181, 2004

Williams I.P. Wu Z. The Quadrantid meteor stream and comet 1491 I, *MNRAS*, 264:659-664, 1993

Williams I. P. Wu Z. The current Perseid meteor shower, *MNRAS*, 269:524-528, 1994

Wu Z. Williams I. P. On the Quadrantid meteoroid stream complex, *MNRAS,* 259:617-628

Wu Z. Williams I. P. The Perseid meteor shower at the current time, *MNRAS,* 264:980-990, 1993

Wu Z. Williams I. P. Leonid meteor storms, *MNRAS*, 280:1210-1218, 1996