NON-LINEAR METEOR TRAILS

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Abstract. In this essay an attempt is made to not only review but reopen the debate on non-linear meteor trails. On the basis of data culled from various, now historical, sources it is found that approximately one in every two hundred of the visual meteors is likely to show a non-linear trail, and that of such trails about 60% will be continuously curved and 40% sinusoidal. It is suggested that two mechanisms may explain the various trail types: the continuously curved trails being a manifestation of the classical Magnus effect, and the sinusoidal trails resulting from torque-free precession.

1. Introduction

Traditionally the majority of meteor data has been recorded through the human eye. While these observations can provide useful statistics on such phenomena as meteor colours, rates and radiants, they are extremely poor at determining such characteristics as meteor velocities, decelerations and durations. It was the introduction, essentially within the last fifty years, of dedicated meteor camera networks, radar and low-light television systems that enabled valuable data on these later parameters to be collected. So, while the human eye is not a particularly useful analytic instrument, it is, under certain circumstances, a very good phenomenological instrument. One particular useful trait is its ability to collect data from a large area of sky. However, as personal experience and general consensus has shown many meteors are initially perceived from the 'corner' of the eye. (This phenomenon has a partial explanation in terms of its physiological structure). Typically a meteor is perceived as a short-lived, straight, and luminous streak, on rare occasions, however, deviations from linearity have been noted. For many years it was thought that this phenomena was due to psychological and physiological effects: being startled through the appearance of a meteor seen peripherally, the reflex head turning and momentary shift of attention results in the perception of an apparently curved meteor trail. The continued sighting of non-linear meteor trails and their eventual photographic recording ultimately forced a reevaluation of the psycho-physiological explanation. In reevaluating the phenomena, however, no clear theoretical model was presented. Below we review the historical debate and data on curved meteor trails in an attempt to gain some physical insight and phenomenological statistics. We also present below two candidate physical mechanisms that may explain the various observed phenomena.

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2. An Historical Survey

The possibility that a small fraction of the meteors can show paths differing from a straight line seems to have been a relatively recent observation. A search through the historic Japanese, Korean and Chinese records assembled by Imoto and Hasegawa (1958) and Tian-Shan (1977) revealed no obvious account of a meteor trail that differed from the linear. This to a certain extent is surprising since the ancient oriental nations placed great importance on the appearance of night sky phenomena. Since there is no reason to suppose that non-linear meteor trails were not seen at this time it may be supposed that it was simply the appearance of a meteor and not its general flight that was important to the court astronomers (Nakagama, 1969). Likewise a search through the meteoric accounts found in the medieval European chronicles compiled by Dall Olmo (1978) yielded no obvious description of non-linear meteor trails. The earliest detailed account of a non-linear meteor trail would seem to date from 1742. As a footnote to a letter concerning a long-lived meteor train observed in 1744, Cromwell Mortimer (1745) comments that on December 16th, 1742 he had observed a meteor from London while in St. James's Park. He explains,

> . . . , I saw a light arise from behind the trees and houses in the S. by W. point, which I took at first for a large sky-rocket; but when it had risen to the height of about 20 degrees, it took a motion nearly parallel to the horizon, but waved in this manner [a sinusoidal curve is drawn] and went on to the N. by E. point over the houses . . . Its motion was so slow, that I had it above half a minute in view . . .

This is a fairly typical account of an observer's impressions upon seeing a bright meteor. Usually there is little detailed information beyond that which is obvious to the observer: colour if any, direction of motion and type of motion, i.e., curved, wavy, straight, fragmentary, etc. Quantities such as magnitude and duration are usually only given by experienced observers. The great period of naked-eye meteor astronomy was set in those years that surrounded the turn and later half of the ninteenth century. A particularly useful collection of meteor data from this period is found in the Reports of the British Association for the Advancement of Science. Between 1848 and 1881 a committee, initially chaired by the Reverend Baden Powell and later by James Glaisher, submitted a series of annual reports on "observations of luminuous meteors (seen) in all parts of the World". A survey of the many meteors described during the thirty-three years over which this committee returned reports has yielded 133 that had paths noted as being non-linear. The data on these meteors is given in Appendix A. On the basis of the information found in the British Association reports a simple, purely phenomenological, classification is proposed and illustrated in Figure 1. Those meteors showing a continuously curved trail are designated as C type, those showing a sinusoidal trail as S type. Meteors which noticeably fragment or split are annotated with an F, those which show abrupt angular changes in their course are marked with an R. There is one instance of a meteor, observed by A. S. Herschel in 1864, that appeared to oscillate about a fixed point. This meteor has been designated ST since it was presumably a sinusoidal meteor seen head on, such meteors usually being called stationary. The percentage distributions of the various

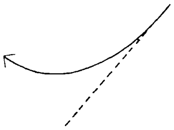
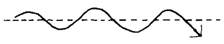
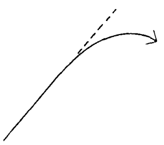
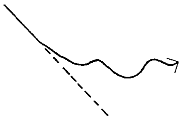
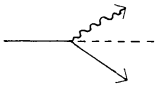
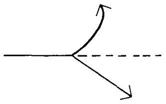
Classification	Typical Appearance	Description
Primary Classification		
C		Continuous curve
S		Sinosoidal
Sub Groups		
CR		Abrupt angular change in direction
CS		Curved sinosoidal
SF		Fragmenting meteor: sinosoidal component
CF		Fragmenting meteor: curved component

Fig. 1. Schematic illustrations of the various trail types.

trail types is given in Table I. This data suggests that of the visual meteors that display non-linear trails about 60% will be curved and 40% sinusoidal. In Figures 2, 3, and 4 the distribution of durations, magnitudes and colours are given. This data is difficult to interpret realistically, there being many psychological and physiological selection effects present in such naked-eye observations. However, it would seem that

TABLE I

Percentage distribution of the various trail types. Data from Table A1.

Type	Total	%
C	67	50.4
CS	5	3.7
CR	6	4.5
All C types	78	58.6
S	52	39.1
SF	2	1.5
ST	1	0.8
All S types	55	41.4

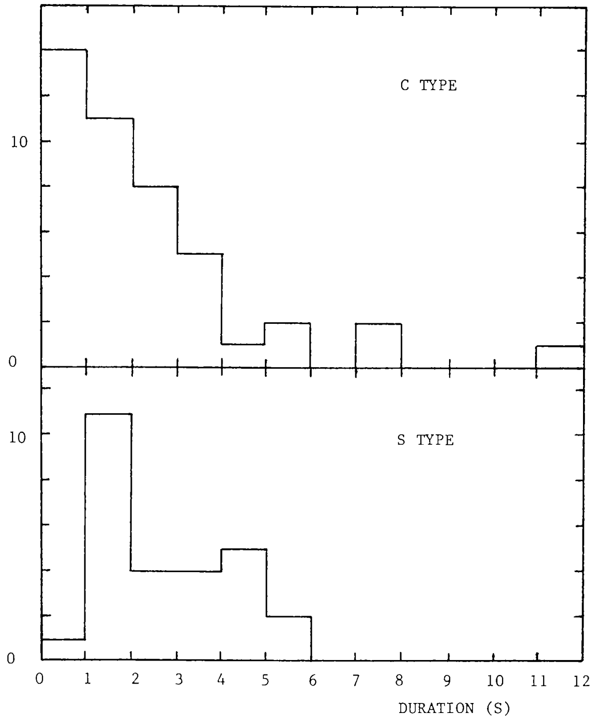


Fig. 2. The distribution of trail durations as found in Table A1.

typically meteors with non-linear trails have durations of between ~1 to ~6 seconds, with the tail of the C type distribution possibly extending to longer durations than the S type. The magnitude distributions are similar, indicating that typically such meteors have magnitudes between +4 and −6 in the visual. All one can probably safely conclude from this is that on average the non-linear trails are produced by bright reasonably long lived meteors. With no velocity estimates it is difficult to interpret this observation in terms of initial meteoroid mass. It is further not possible to interpret the meaning and significance of meteor colours in any useful way at the present time (Beech, 1987). Figure 4 simply indicates that C type meteor trails are more likely to be blue than yellow, which is the typical colour of an S type trail. Red meteor trails are thought to be those that reflect sunlight and so a certain number of such trails is expected. White is the typical colour sensation that a meteor invokes in the eye and as such the high percentage of trails described as having this colour is also expected (Beech, 1987).

The British Association reports on 'the luminous meteors' offers no pretence at completeness, and as such it is not possible to estimate from that source the frequency of non-linear trails amongst the visual meteors. However, among those experienced and dedicated meteor observers who worked in the early years of this century, W. F. Denning and C. P. Olivier, have given data that is useful for this purpose. Their observations are summarized in Table II, from which it would seem that about 0.54% of the visual meteors, or roughly one in two hundred, will show a non-linear trail.

The advent of celestial photography in the late 1880's inevitably resulted in the accidental capture of meteor trails. Fisher and Olmsted (1931) found in a study they

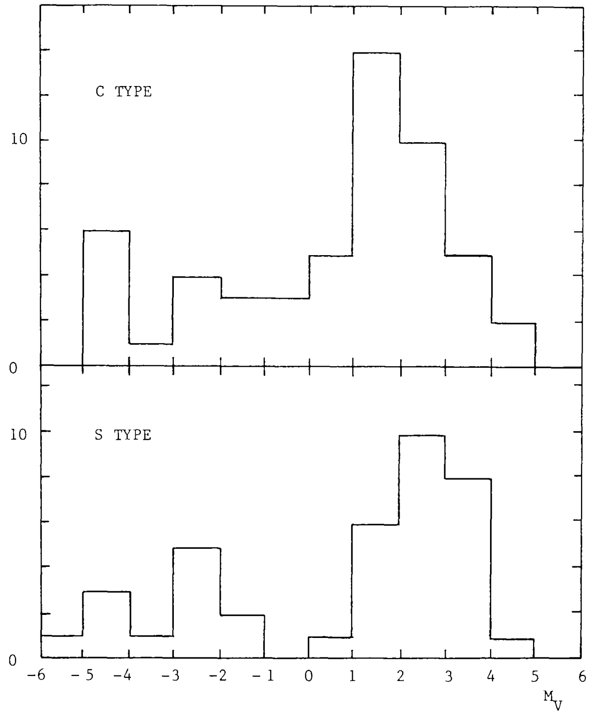


Fig. 3. The distribution of maximum magnitudes as found in Table A1.

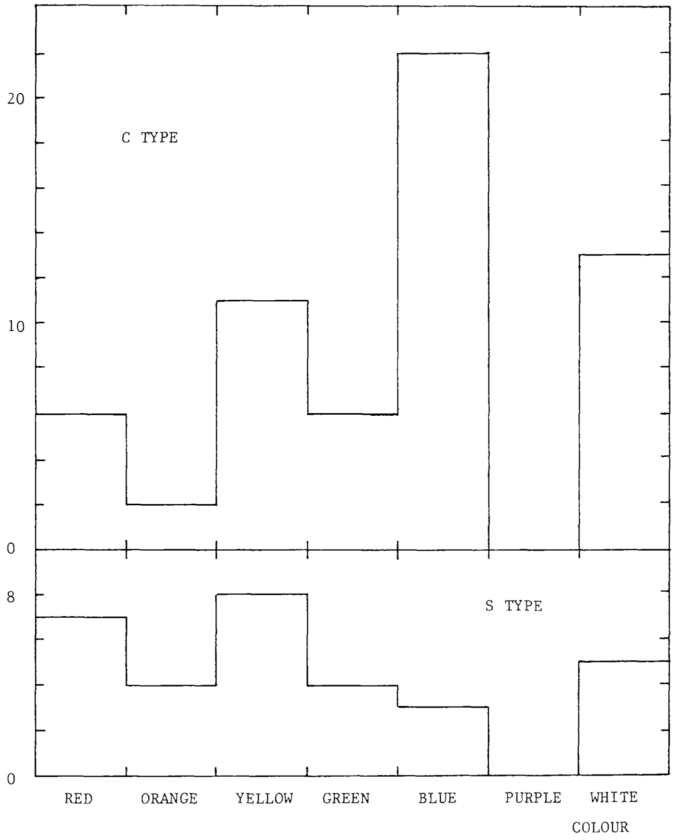


Fig. 4. The distribution of trail colours as found in Table A1.

TABLE II

Percentage of non-linear meteor trails observed during various years according to Denning (1887) and Olivier (1925).

Year	Meteors Observed Total	 Non-Linear	 %	Reference
1885	1334	4	0.30	Denning (1887)
1886	1431	15	1.05	Denning (1887)
1900	436	4	0.92	Olivier (1925)
1901	526	5	0.95	Olivier (1925)
1902	244	1	0.41	Olivier (1925)
1903	731	2	0.27	Olivier (1925)
1904	787	1	0.13	Olivier (1925)
1906	375	1	0.27	Olivier (1925)
1909	1213	5	0.41	Olivier (1925)
Total	7077	38	0.54	

conducted an archival Harvard Observatory plates that one meteor image (recorded on October 20th, 1922) out of a total of 386 captured showed a type S trail. A second study of Harvard plates by D. Hoffleit (1937) found that of a further 217 meteors recorded two showed type S trails. These studies suggest that 3/603 or 0.5% of the photographic meteors, that is roughly one in two hundred images, will show an S type trail. This result is surprisingly high since it is not expected that the visual and photographic meteor rates will be comparable (Millman, 1936). The high photographic rate probably attests to the fact that many more of the apparently linear meteor trails observed with the unaided eye are in fact sinusoidal, the eye being unable to record the slight variation. The inference of this result is that a much higher proportion of the visual meteor trails are in fact S type. To the author's knowledge no C type trail has ever been photographed.

The debate concerning non-linear meteor trails does not occupy a large fraction of the astronomical literature. The first article that specifically addressed the non-linear meteor trail phenomenon appears to be by B. J. Hopkins (1885) who commented that,

> There is a, . . . , class of meteors that I have occasionally observed, though never found described in the text-books, which differs from those usually seen in that they travel in a zigzag or wavy path; from which circumstance and the rarity of their appearance I propose designating them 'erratic' to distinguish them from the ordinary meteors, which, . . . , they resemble in every other particular.

In a second paper on "erratic meteors" Hopkins (1886) comments that in response to his first communication A. C. Raynard had suggested it was the irregular shape of some meteoroids that led to them describing curved paths. W. F. Denning was not happy with either Hopkins's terminology or Raynard's explanation. In Denning (1887) he writes,

> The term 'erratic' applied by Mr Hopkins to such meteors as display curved paths appears to me inappropriate. Erratic meteors are usually understood to refer to such of those bodies as belong to unknown

> systems, and are therefore synonymous with sporadic meteors . . . The term adopted by Mr. Hopkins is not expressive of the peculiarity to which he refers it. Such words as devious, sinuous, deflected, or tortuous meteors would be preferable, as conveying a distinct idea of the anomalous flights alluded to.
>
> As a rule, I believe the alleged crooked paths are nothing more than mere impressions. The curious flickering in the light of individual meteors often gives rise to considerable alterations in their apparent brilliancy, combined with the fact that these phenomena rarely last long enough to ensure a steady view, occasion the idea of curved flights. The observer is seldom looking towards the exact place of a meteor's course, and the glimpse he obtains is more or less hurried, imperfect, and erroneous.

This lengthy quotation is noteworthy, since its sentiments dictated the common opinion for many subsequent years. Respect for Denning's authority and reputation as a meteor observer were such that Hopkins's terminology was not adopted or referred to in any future debate, and the general consensus seems to have sided with Denning in suspecting that the curved meteor trails, in most cases, were nothing more than optical illusions. Certainly, the initial debate on non-linear trails ended with Denning's comments. Some thirty-eight years later, however, C. P. Olivier (1925) in his classic treatise, 'Meteors' returned briefly to the subject and argued that curved trails were quite real phenomena. On the assumption that the meteoroids are irregular in shape Olivier drew analogies with the flight of boomerangs, the flight of tumbling artillery shells, and the 'skipping' of flat stones, when thrown correctly, on the surface of still water. He explains,

> From these well known illustrations it is quite easy to see that a non-spherical meteor, . . . , will in general rotate about some axis after encountering the resistance of the air, and may have its course completely changed from an approximate arc of a great circle to a number of curious forms . . .

Interestingly, Olivier is suggesting that it is only the irregular shape of meteoroids that is initially important. The rotation that they acquire is due solely to their shape and their interaction with the Earth's atmosphere. An analogy can be drawn here with the path of an irregular shaped stone falling through a column of water. Indeed, experiments performed by Paddack (1969) found that centimeter sized stones when dropped through a column of water (his swimming pool) acquired a spin about the axis that lay along the direction of fall. This experimental result is more interesting than it may at first seem since it is currently thought that a similar process with solar radiation acting as the 'fluid' is responsible for induction of meteoroid spin in interplanetary space (Ratcliff *et al.*, 1980). With the increasing stock of meteor trails recorded photographically it was possible in the 1930's to attempt detailed analyses of individual meteors. Fisher *et al.* (1927), for example, considered two meteor trails that displayed periodic flickering. While their analysis concludes that the trails were straight, their Figures 2 and 3, would seem to indicate sinusoidal paths (Fisher *et al.* (1927) dismiss the deviation from linearity as being due to catalogue and mensuration error). As to the variations in trail brightness they comment, "Periodic flickering might be due to non-homogeneous composition of the meteor, combined with rotation; . . . one flash for each rotation. . . " They later qualify the rotation hypothesis and argue, ". . . to the whole rotation hypothesis there is an objection, that the beginning of a trail is always a hair-line with no spindles [bright marks] for some distance. More information is needed." Indeed more information was and still is required! Shortly after Fisher *et al.* (1927) presented their work, M. Olmsted (1932) analysed, ‘an unusual meteor trail’. This meteor displayed a type S trail that periodically ‘flickered’. Olmsted’s analysis suggested that there were seven ‘flickers’ per trail wavelength, and she suggests;

> To explain such an appearance in a meteor trail, it might be suggested that a flat or unevenly shaped object, large enough to remain partly solid during the observed portion of its flight, had met with uneven resistance of the air, or, blowing off a jet of gases, had rotated and formed a spiral train. . .

Here the common idea of irregular shape is supplemented with the possibility of ‘jet’ formation. This suggestion draws on an analogy with the flight of a ‘Guy Fawkes’ rocket. Ideas pertaining to the cause of curved meteor trails advanced very little over subsequent years, and in his general review of unusual meteors Millman (1935) simply comments that curved and sinusoidal meteor trails, “. . . probably arise from the rotation of an irregular shaped mass. . .”

The study of curved meteor trails has seemingly always been a minor part of meteor astronomy. This is not surprising given the rareness of their appearance and the almost complete lack of detailed information on the phenomena. Since the late 1930’s, however, the subject seems to have sunk even deeper into obscurity. There is no mention, for example, of S or C type trails being recorded by any of the various camera networks that operated with spectacular success in the 1950’s. From the analysis above, it is unlikely that none were recorded, presumably they were passed over for the sake of other studies. Indeed a re-analysis of such photographic data may be very rewarding!

3. Curved Trails (C type)

So far our study has focussed on the historical debate and observation of non-linear meteor trails, we now consider some physical mechanisms that may possibly explain the observations. It is suggested, in fact, that two mechanisms may be at work: the curved or C type trails are a manifestation of the Magnus effect, while the sinusoidal or S type trails result from torque-free precession. We consider each mechanism in turn.

The Magnus effect, in all but name, is familiar to those athletes whose sport involves the use of a ball. It is well known that if some spin is imparted to a ball its flight path will be curved. The ball will deviate from the ‘normal’ path in the same direction as that in which the forward face of the ball spins. This spin induced deviation is named after the German physicist, H. G. Magnus who in the mid-nineteenth century noted the effect in the trajectories of spinning cannonballs. A clear description of how the Magnus effect operates is not currently available. This is so since the effect is dependent on aspects of boundary-layer turbulence, a phenomena which in the words of Birkhoff (1960), “. . . has so far defied mathematical treatment as a boundary-value problem. . . ” However, from wind tunnel experiments on small spheres (baseballs), Briggs (1959) found that the lateral force F_M that gives rise to the

Magnus deviation is proportional to the sphere's rotation rate w and the square of the wind speed, i.e.,

$$F_M = k_M v^2 w \tag{1}$$

where k_M is a constant. On the basis that this lateral force is continuously applied in a direction perpendicular to that of the motion, the deviation S in time t of a sphere of mass M will be

$$s = v_0 t + \frac{1}{2} a_M t^2, \tag{2}$$

where a_M is the acceleration due to F_M. With $v_0 = 0$, $F_M = Ma_M$ and substitution from (1) the lateral deviation is expressed as

$$s = kv^2 t^2 w / M, \tag{3}$$

where $k = k_M/2$ is a constant. Now, on the basis that the Magnus effect is the cause of type C meteor trails, Equation (3) offers in principle a measure of w, the meteoroid rotation rate. This is so since the deviation, s, the velocity, v, the time, t, and meteoroid mass, M, are in practise observable or deducible from photographic meteor light curves. While Equation (3) may be useful in principle, the observational rarity and the complete lack of detailed data on such meteor trails unfortunately eclipses its applicability at the present time. However, it is to be hoped that relevant data will eventually become available.

Two ingredients that must be present for the Magnus effect to operate are meteoroid sphericity and spin. It seems likely that the latter condition is satisfied. Meteoroid rotation has been invoked as an explanation for the initial large width of radio meteor trains (Hawkes and Jones, 1978), and as recently demonstrated by Olsson-Steel (1987), the Yarkovsky-Radzievski effect, essentially a consequence of meteoroid rotation, may be an important perturbative force in meteor stream evolution. As for meteoroid sphericity the observations are less clear. Typically, a meteoroid is thought of as a rather open, fragile, conglomerate structure, and most often simply called a 'dustball'. This structure results partly from the initial accretion process (Daniels and Hughes, 1981; Beech, 1987) that produced the meteoroid and partly from the collisional history that the meteoroid has undergone (Kapišinský, 1987). Visual comparisons with the sampled Brownlee particles (Brownlee, 1978) suggest that near sphericity is a common form. Daniels and Hughes (1981) found in their accretion simulations that sphericity was the general rule, but that deviations from sphericity occurred in about 1/3 of their conglomerates. It would appear in practise then that at least the necessary conditions for the Magnus effect to operate are likely satisfied. It is clear, however, that spin and sphericity are not sufficient conditions for the production of type C trails, since these attributes are common to most meteoroids and only a small percentage of meteor trails display noticeable non-linear effects. Such factors as meteoroid velocity, mass and cohesion (i.e., the melting point of the 'glue' in the Hawkes-Jones (1975) meteor model, see also Beech (1986)) are no doubt also important factors. If a meteoroid is distinctly non-spherical, i.e., disk shaped or ellipsoidal then a new mechanism may come into play and it is this we discuss next.

4. Sinusoidal Trails (S type)

As is clear from the discussion in Section 2 the S type trails are phenomenological quite different from those of type C. We further argue here that the type S trails are the result of a process different to that of the Magnus effect. Since the Magnus deviation operates in a fixed plane, i.e., the plane containing the axis of meteoroid spin, it is topologically impossible for the resultant curvature to describe a sinusoidal form. A trail showing periodic loops or cusps is the only possible form that the Magnus effect can produce. The sinusoidal feature of S type trails is then either the projection of a planar wave or a spiral. Some evidence that the motion is in fact spiral may be found from observations of stationary meteors. Such meteors are again only rarely observed. The catalogue of Denning (1879) lists the positions of 222 stationary meteors, which was the total found from a collection of catalogues listing 59028 meteors. In this manner 0.4%, or roughly one in two hundred and fifty of the visually observed meteors will appear stationary. Interestingly, however, in a second catalogue Denning (1923) notes, "... meteors near stationary are usually slow, [and] often display a curling or tortuous movement..." This observation suggests that some of the stationary meteors may in fact be the projection of a spiral trail seen head on. Further evidence of spiral motion follows from an account given by A. Dinsmore, who witnessed the fall of a meteorite in Nobleborough, Maine (U.S.A.) on August 7th, 1823. The event is described in Cleaveland (1824), who writes:

> ... Mr. Dinsmore's attention was excited by hearing a noise which at first resembled the discharges of platoons of soldiers, but soon became more rapid in succession. The air was perfectly calm, and the sky was clear with the exception of a small whitish cloud, ..., nearly in his zenith, from which the noise seemed to proceed... this little cloud appeared to be in rapid spiral motion downwards as if about to fall on him, and made the noise, like a whirlwind among leaves...

On the basis of the above observations, it is possible that the type S trails are in fact spiral trails (luckily the nomenclature of trail type still holds!). This spiral like trajectory may be explained in terms of torque-free precession. Important to this form of motion, besides being torque-free, is that the body is spinning and non-symmetrical. A physical and visually useful analogy to this situation is a rugby or American football spinning about its long axis. As we discussed in section 3 both of the conditions of non-sphericity and spin are likely to be satisfied by some meteoroids.

The equations describing torque-free precession can be found in any standard textbook on classical mechanics, see, e.g., Barger and Olsson (1973). If, for simplicity, one considers a cylindrically-symmetric rigid body spinning about its long axis with angular velocity w_z, then in the absence of external torques the Eulerian equations of motion can be solved in terms of simple trigonometric functions. Further, the precession frequency $w_p/2$ can be related to the spin angular velocities as

$$w_p = w_z \left\{ \left(\frac{I_z}{I_{xy}} \right)^2 + \frac{w_x^2 + w_y^2}{w_z^2} \right\}^{1/2}, \tag{4}$$

where I_z and $I_x = I_y = I_{xy}$ are the principle moments of inertia with respect to the axis of symmetry (x, y, z), and where w_x, w_y, w_z are the components of the angular velocity $\bar{w}$. With the spin aligned along the z axis of symmetry and $w_x = w_y = 0$, Equation (4) gives the rate of precession to the rate of spin as

$$\frac{w_p}{w_z} = \frac{I_z}{I_{xy}}; \tag{5}$$

that is, the ratio w_p/w_z is determined by the ratio of principle moments of inertia, which are in turn determined by the shape of the body.

Once again, a satisfactory comparison between the predictions of Equation (5) and observations is frustrated through a lack of detailed meteoroid knowledge. In principle w_p can be determined from the wavelength of the meteor trail, but at this stage w_z and the shape determined principle moments of inertia are unknown.

5. Conclusions

In this essay we have attempted to review the historical debate and data concerning the non-linear meteor trails. As such a phenomenological classification has been suggested and two physical processes have been outlined as possible mechanisms that explain the limited observations. In spite of the discussion in Sections 3 and 4 we are still in the uncomfortable position of not being able to explain why only a small percentage of meteor trails are non-linear. The mechanisms offered as an explanation for the C and S type trails are reasonably well-known processes, each of which has a host of everyday example phenomena to attest to their operation: the curved tennis backhand, and the spiral path of a thrown American football being just two examples. At present it is not certain that these processes can even be expected to operate at the high velocities and under the extreme conditions of meteor ablation. Clearly further constraints on the non-linear trail phenomena have as yet to be identified, excitingly, however, it may be possible to constrain these through laboratory experimentation. An analysis of photographic meteor trails probably offers the best possibility for determining non-linear trail characteristics. Specifically at this stage, two station observations would be most welcome. In this way true heights and trajectories may be determined. Likewise, the velocity and decelerations of such meteors are at the present time completely unknown and in need of annotation. The all too familar cry of 'more observations' is once again used as a concluding comment and plea!

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Appendix A

In this section the data on non-linear meteor trails, culled from the reports of the British Association, are presented. This data is contained in the volumes published between 1848 and 1881, and displayed in Table A1. This table is mostly self explanatory, however, the times in column 3 are PM unless marked with an A which signifies an AM observation. Column 4 gives the magnitude or estimated brightness as given by the observer (column 8). Column 7 specifies the trail type. The various types are illustrated in Figure 1 and correspond to continuously curved, *C*, and sinusoidal, *S*, paths. These terms are further qualified as *CS*; which is a curve and sinosoidal composite, or *CR*, which designates that an angular, rather than smooth, curve was described, or as *SF*/*CF* which corresponds to a fragmented or split meteor, one fragment of which showed an *S* or *C* type trail. ST corresponds to a meteor seen nearly head on, as if stationary.

TABLE A1

Year	Date	Time	Magnitude	Colour	Duration	Type	Observer
1841	Dec. 10	–	=2	–	–	S	J. F. W. Herschel
1846	Sept. 25	10:00	–	–	–	CS	E. J. Lowe
1847	Nov. 19	4:30A	–	–	–	S	G. J. Symons
1848	Aug. 9	11:37	–	–	–	CR	Bombay Times
1849	June 27	11.33	=Jupiter	Yellow	–	C	E. J. Lowe
1849	Aug. 10	10:10	–	–	–	S	W. H. Leeson
1849	Aug. 12	–	–	Gold	–	S	W. H. Lesson
1849	Nov. 1	11:00	–	–	–	C	T. W. Webb
1849	Nov. 2	5:33	1/8 Moon	Orange	~30	C	E. J. Lowe
1850	Feb. 11	11:42	–	Greenish	~5	S	F. Barnard
1850	Aug. 29	10:07	> 2	Blue	1	CR	E. J. Lowe
1850	Oct. 15	11:05	=2	Blue	0.5	C	E. J. Lowe
1850	Dec. 9	–	4 × 1st	–	–	C	T. Rankin
1852	April 20	11:35	=4	–	–	CS	J. Slater
1852	May 14	10:30	=Vega	White	–	C	J. Slater
1853	Aug. 9	10:09	=Mars	Red	–	SF	W. R. Birt
1853	Aug. 9	10:34	=2	–	–	S	W. R. Birt
1853	Aug. 9	10:54	=1	–	–	C	W. R. Birt
1853	Aug. 9	11:02	=Jupiter	–	–	C	W. R. Birt
1853	Sept. 25	7:11	=Jupiter	Orange	–	S	F. V. Fassel
1855	Aug. 1	10:52	1/4 Moon	Blue	–	C	E. J. Lowe
1855	Dec. 13	9:10	=3	–	–	S	G. J. Symons
1856	June 4	11:05	=3	–	–	S	G. J. Symons
1856	Aug. 7	9:48	=3	–	–	S	G. J. Symons
1856	Aug. 10	10:05	=3	–	–	S	G. J. Symons
1856	Aug. 10	1:22A	=1	–	–	S	G. J. Symons
1857	July 24	11:34	2 × Sirius	–	–	S	G. J. Symons
1857	July 25	10:32	=3	–	–	S	G. J. Symons
1857	July 27	10:35	=1	–	–	S	G. J. Symons
1857	Aug. 28	10:44	=2	–	–	S	G. J. Symons
1858	Jan. 10	8:17	–	–	–	C	W. Braithwaite
1858	Aug. 1	12:35A	=2	White	–	S	G. J. Symons
1858	Aug. 12	12:41A	=1	Yellow	–	CR	G. J. Symons
1859	Sept. 27	8:15	2 × 1st	Blue	0.1	C	E. J. Lowe
1860	March 10	9:00	–	Green	–	C	R. P. Greg
1860	April 14	9:04	=Aldebaran	–	–	C	J. Herschel
1861	April 10	10:25	–	White	–	S	R. P. Greg
1861	Aug. 6	11:21	>Venus	Bluish	~2	C	J. Baxendall
1861	Aug. 9	10:41	=3	–	0.2	C	E. J. Lowe
1861	Nov. 12	5.48	–	Greenish	–	C	G. Wedgewood
1861	Nov. 19	9:45	–	–	10–12	C	J. Chapman
1861	Dec. 1	9:14	≈ Polaris	Yellow	3	S	H. S. Eaton
1862	Jan. 11	7:05	> Venus	Yellow	–	C	W. R. Birt
1862	Jan. 11	11:48	=Jupiter	Yellow	3	S	W. H. Wood
1862	Feb. 2	9:15	2 × Venus	White	2	C	D. Walker
1862	Feb. 12	11:32	=4	Yellow	0.2	S	A. S. Herschel
1862	April 29	11:55	1/2 Jupiter	Red	4.5	S	A. S. Herschel
1862	Aug. 5	9:43	~Venus	Yellow	1.5	S	W. H. Wood
1862	Aug. 12	1:30A	=Arcturus	Red	1	C	A. S. Herschel
1862	Sept. 22	10:23	=4	–	–	C	F. Howlet

TABLE A1 (continued)

Year	Date	Time	Magnitude	Colour	Duration	Type	Observer
1862	Sept. 22	10:23:30	=4	–	–	C	F. Howlet
1862	Sept. 27	–	–	–	–	S	"Kent & Sussex Advertiser"
1862	Sept. 29	8:49	~Mars	Bluish	2	S	J. Baxendall
1862	Oct. 26	7:45	–	Orange	~1	S	J. Baxendall
1862	Nov. 11	7:10	=1	White	–	C	T. Humphrey
1863	Feb. 14	9:00	–	–	–	S	R. P. Grey
1963	March 7	7:35	=1	Red	~7	CS	W. H. Wood
1863	June 1	11:30	> Sirius	Red	4	CS	W. H. Wood
1863	Aug. 11	10:33	=3	Yellow	2	S	W. H. Wood
1863	Sept. 4	10:13	=2	Red	0.7	C	T. Crumplen
1863	Dec. 2	9:29	=1	Yellow	3	S	W. H. Wood
1863	Dec. 5	~8 pm	=full Moon	–	Few	S	"The Scotsman"
1864	Feb. 3	10:30	δU. Maj	–	–	C	H. Grounds
1864	April 10	9:42	=Capella	Orange	0.8	C	A. S. Herschel
1964	July 29	10:45	=1	Blue	< 1	C	W. C. Nash
1864	Aug. 10	12:21A	=2	Blue	1	C	W. C. Nash
1864	Sept. 27	8:52	=Vega	Yellow	3.8	S	A. S. Herschel
1864	Nov. 7	3:13A	=1	Yellow	1	ST	A. S. Herschel
1865	Feb. 17	10:04	=3	Blue	0.5	C	W. C. Nash
1865	May 25	1:04A	=1	Blue	1.5	S	W. H. Wood
1865	July 28	11:32	=1	Orange	1.8	S	A. S. Herschel
1865	Aug. 11	11:17	=2	Blue	–	C	A. Harding
1865	Sept. 16	10:20	~Venus	Yellow	3–4	C	T. W. Webb
1865	Oct. 13	6:30	=2	Blue	1.5	C	W. C. Nash
1865	Oct. 20	11.01	=3	Orange	1.2	S	A. S. Herschel
1865	Oct. 25	6.01	3 × 1st	Blue	2	C	A. Harding
1865	Nov. 13	12:29A	> Jupiter	–	–	S	F. Howlett
1865	Nov. 15	8:38	=2	Bluish	1	C	T. Wright
1865	Dec. 14	8:09	=2	Blue	2	C	A. Harding
1865	Jan. 9	9:38	=1	White	1	C	T. Wright
1866	Feb. 13	12:00A	5 × αPer	Blue	3.5	CR	T. Crumplen
1866	March 16	10:12	=Rigel	Yellow	3	C	T. Wright
1866	April 14	9:36	=1	Bluish	–	C	A. Harding
1866	May 7	9:53	=3	White	1	S	T. Wright
1866	July 15	11:20	=2	White	0.8	C	T. Crumplen
1866	July 22	11:40	=2	Yellow	1.3	S	A. S. Herschel
1866	Aug. 9	11:06	=Sirius	White	0.3	CR	W. H. Wood
1866	Nov. 10	5:10A	=2	White	1	S	A. S. Herschel
1866	Nov. 12	2:04A	=2	Blue	0.7	C	T. Crumplen
1866	Nov. 13	9:18	2 × Jupiter	Yellow	3.5	C	J. E. Clark
1866	Nov. 14	3:20A	=Mars	Red	–	S	C. F. Penrose
1866	Nov. 27	6:20A	=Jupiter	Greenish	1	C	J. E. Clark
1866	Dec. 4	8:23A	=1	Yellow	0.25	C	J. E. Clark
1866	Dec. 10	7:01	=Jupiter	Yellow	1.5	C	J. E. Clark
1866	Dec. 12	8:23	=Venus	Green	1.5	S	J. E. Clark
1866	Dec. 13	11:45	=2	–	1.5	S	W. H. Wood
1867	Feb. 6	9:29	=Sirius	Red	2.5	S	J. E. Clark
1867	July 31	12:25A	=1	White	1.6	CS	A. S. Herschel
1867	Sept. 3	10:40	=3	Blue	1	C	W. H. Wood
1867	Sept. 15	11:04	–	Red	–	S	A. Finch

TABLE A1 (continued)

Year	Date	Time	Magnitude	Colour	Duration	Type	Observer
1867	Sept. 22	10:15	=3	Blue	1.5	C	W. H. Wood
1867	Oct. 29	~9pm	–	Red	< 1	C	G. Haley
1868	May 20	12:33A	=1	White	1.5	C	W. H. Wood
1868	May 28	12:39A	=2	Red	3.5	S	A. S. Herschel
1968	Aug. 10	11:54	=1	White	–	C	G. H. Griffith
1868	Sept. 10	10:11	=3	White	–	C	W. Jackson
1868	Oct. 18	~10pm	–	–	–	C	W. Jackson
1868	Nov. 8	6:27	=1	Red	4	S	J. E. Clark
1868	Nov. 15	6:22	=2	White	4	S	A. K. Brown
1868	Dec. 12	12:34	=1	Red	3	C	W. H. Wood
1869	June 10	11:00	=1	White	0.3	C	A. S. Herschel
1869	Aug. 8	8:45	=Sirius	White	1	C	A. S. Herschel
1871	Oct. 8	10:28	~Venus	White	–	C	G. J. Symons
1872	March 4	7:45	> Venus	Greenish	2.5	C	T. Perkins
1872	Oct. 9	12:00A	~Venus	Yellow	–	C	T. W. Webb
1873	Aug. 2	10:28	2 × Jupiter	Green	3	S	J. Lucas
1873	Aug. 11	9:12	=1	Yellow	2.5	C	J. Lucas
1874	Jan. 7	5:07	–	Greenish	5–6	C	T. Perkins
1875	Dec. 22	1:38	–	–	–	C	A. J. Powell
1876	July 25	10:02	2 × Jupiter	Blue	~7	CR	H. Pratt
1876	Aug. 4	10:17	–	–	4	S	J. Thomson
1876	Aug. 15	9:35	> Jupiter	Yellow	–	C	E. W. Binney
1876	Nov. 6	~9pm	–	Red	–	SF	T. Nostro
1876	Nov. 8	5:05	–	Bluish	–	C	F. C. Penrose
1877	Jan. 7	10:31	~Venus	Yellow	5–6	S	W. H. Wood
1877	April 16	10:50	3 × Venus	Bluish	1–2	S	F. T. Mott
1877	Nov. 16	9:14	~Venus	Blue	2.5	C	E. Pickard
1878	Jan. 31	11:20	> Venus	Bluish	2.25	C	W. H. M. Christie
1878	April 2	7:55	–	Yellow	–	S	F. T. Mott
1878	April 12	8:53	–	–	5–6	C	J. T. Sewell
1878	May 27	7:30	15 × Venus	Green	–	C	W. A. Sanford
1879	June 7	~10pm	~full Moon	Greenish	–	S	Nature **20**, 1879