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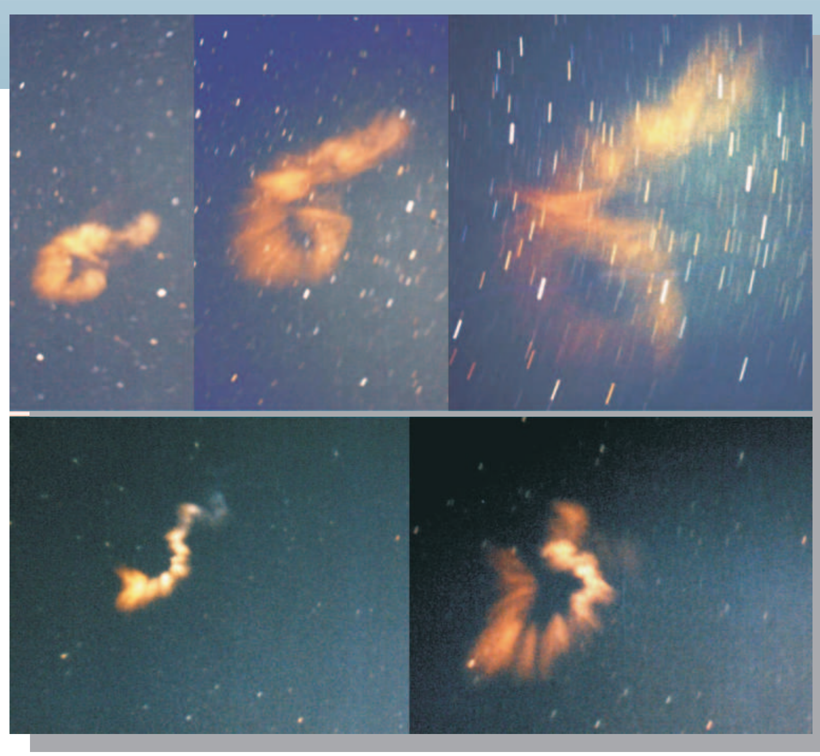

Quadrantids
Radio Perseids
Persistent trains
Spanish fireballs
IMC 2003 Proceedings

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Front cover photo

Leonid persistent trains photographed by Valentin Grigore of SARM, Romania on 1998 November 16/17 in Targoviste, Romania.

Top row: from a magnitude −15 Leonid fireball at 01^h43^m in Ursa Major; train visible for 25 minutes.
Frame 1: 60 s, starting at $01^h52^m20^s$ UT; frame 2: 135 s, $01^h53^m45^s$; frame 3: 360 s, 01^h56^m.
Lens: f=50 mm, $f/1.8$; film: Kodak 400 ASA.

Bottom row: from a magnitude −15 Leonid fireball at 04^h10^m in Coma Berenices; train visible for over 15 minutes despite limiting magnitude worse than +4 because of dawn.
Frame 1: 30 s, $04^h10^m20^s$; frame 2: 60 s, $04^h11^m00^s$.
Lens: f=50 mm, $f/1.8$; film: Kodak 400 ASA.

Cover design
Rainer Arlt

Janus

Mihaela Triglav-Čekada

We have to look back as we start the 32nd volume of WGN. Last year's volume was prepared by the new editor Chris Trayner. He put a lot of effort and time into the new style and editing of WGN. We have to say that all six numbers came out on a regular basis and with a lot of interesting articles. As Chris is doing the editing totally voluntarily, we have to thank him in some way. I propose to the readers of WGN that in a manner of gratitude, think about and then write some new interesting article, even those who never wrote any articles for WGN. That will revive the contents of WGN and, in a way, tie the readers and IMO members together. Do not say, 'I am not doing anything special, I cannot write an article'. Everybody can write something about his observing experiences, his meteor or astronomical organisation in which meteor observers gather in his country ... and all that, I think, will be of great interest to a lot of readers of WGN. Everyone is anxious to learn from others' experiences and wants to know what his colleagues in his neighbouring countries are doing. Do not just say, 'I do not know how to write an article', as I will point you directly to Trayner's instructions for writing papers for the WGN in issue 31:4 (pp. 124–128), where all is explained in detail. But on the other side, we also need scientific papers, so that WGN will remain colourful with its contents, so write those also.

At this point we have to thank also the old group of IMO officials for their splendid work on co-ordinating the big international organisation which IMO is. We must hope that enthusiasm for meteor-related works among Council members and others who help the organisation will remain for many years to come. If you think you can help the IMO in some way, do not hesitate and contact our president Jürgen Rendtel, and discuss your plans with him. All the help will be much appreciated. I think that the beginning of a year is a great turning point to start working on new things and getting involved in things where you just thought, 'maybe, someday, when I will have time, I will start helping the IMO'. You have as much time as you are prepared to sacrifice for other stuff, so that should not be an obstacle for doing interesting things.

On the other side, do not forget to observe meteors in 2004, even though the great show of the Leonids is over: I believe that a lot of interesting meteor outbursts of small meteor showers are just waiting there to be observed or to be investigated.

Janus *was a Roman god with two faces, one looking to the past and one to the future, called upon at the beginning of any enterprise. Today he is often a symbol of re-appraisal at the start of the year.*

Editorial

Chris Trayner

This issue sees the second in our series of occasional **Fundamentals of meteor science** papers, this time written by Prof. Iwan Williams of Queen Mary College, which is part of the University of London. I am grateful to Iwan for writing this article, which springs from a talk he gave at the Open University last year.

This issue is appearing somewhat late, for which I apologise. Work on the IMC 2003 Proceedings has taken a lot of my time (and far more for Mihaela Triglav-Čekada, the Proceedings Editor). Next year, with luck, it will be possible to schedule this work differently and avoid a delay to WGN 33:1.

For practical reasons, Rainer Arlt's annual tabulation of solar longitudes has been delayed until the next issue.

Photography Competition — Results

Last year we announced a competition for the best photographic material submitted to WGN.

We are pleased to announce that the prize has been won by Pavel Spurný. Pavel has submitted several spectacular photographs of fireballs (WGN 31:2 pp. 53–54 & back cover, 31:6 pp. 171–173 & back cover). Rather than choosing the book in advance, we decided to let the winner select a book of their choice.

Part of the front and all of the back cover of WGN are available for photos, which need not be related to any article. The front cover can be colour, though this depends on us having worthwhile colour photos to print. Here is an opportunity to see your work reproduced in good quality. Submission details can be found inside the front cover.

Conferences

Details of the Proceedings of IMC 2003, Bollsmannsruh, Germany

Those who have attended an International Meteor Conference (IMC) will know that they present many high-quality papers on a wide range of meteor subjects. This material is less well known outside the circle of conference-goers, however. To make it more widely available, we are publishing brief details of all IMC 2003 papers here.

Those who attended the Conference will soon receive the Proceedings. Others can order them from the IMO: details are in the lower half of the inside back cover of this Journal.

FIFIE — Fireball Filming Equipment — All sky imaging with video

Felix Bettonvil

This contribution revolves around the construction of a video camera equipped with a fisheye lens for the observation of fireballs. The described camera FIFIE (Fireball Filming Equipment) will be installed in Utrecht, centrally located in the Netherlands, being able to witness any fireball sighting above the lowlands. It is a valuable support for visual fireball reports as it can provide accurate timing. Such a camera must be seen as an addition to photographic all-sky cameras because its lower spatial resolution cannot replace them. On the other hand, the effort to make such a camera operational is reduced to a minimum. It has the potential to be used by a much larger group of meteor observers, improving the quality of a fireball network too.

Model of the ablation of faint meteors

Margaret D. Campbell-Brown, Detlef Koschny, Joe Zender, Oliver Witasse

A model of meteor ablation in the atmosphere has been developed for meteoroids in the mass range 10^{-12} kg to 10^{-5} kg (size range 10 μm to 1 mm). The model builds on the classical model of meteor ablation, and adds a thermal fragmentation mechanism. The goal of the model is to characterize the physical structure (fundamental grain sizes) and chemical composition of meteoroids.

Meteor Orbit and Trajectory determination Software (MOTS) Theoretical background: purpose, requirements and algorithms

Jorge Díaz del Río, Detlef Koschny

The Meteor Orbit and Trajectory determination Software (MOTS) is an application which determines the trajectory and orbital parameters of a meteor using data obtained with the METREC software or in the same format. The algorithm used in this software is explained, as well as the objectives of the application and the requirements to perform the computations.

Five wild years Reminiscences of the Leonids experience 1998 – 2002

Daniel Fischer

This is not a scientific review of the surprises, discoveries and sensations the Leonids brought from 1998 to 2002, but a look back by one observer (and science writer) who often witnessed first-hand what went on in the sky — and also how science finally got its grip on the elusive and striking phenomenon of meteor storms. It was a truly an experience with a deep impact (no pun intended) that is not likely to be repeated...

Meteor poetry dramas played in Romania

Andrei Dorian Gheorghe

Perseide 2003 event and summer meteor observations in Romania

Valentin Grigore and Ştefan Berinde

Observations of the 2002 Leonids by the MBK Team

Javor Kac

The *MBK Team* organized another Leonid expedition in 2002. The meteor storm was observed from the French Alps, employing visual, photographic and video techniques. Visual observation results from five observers covering 18.2 observing hours with more than 5500 Leonids are presented. The peak ZHR of 3600 was reached on 2002 November 19, $04^{\rm h}10^{\rm m}$ UT ($\lambda_\odot = 236\overset{\circ}{.}616$). Video observations covered only the ascending branch of the peak and are in agreement with the visual data. The Leonid activity was also recorded via forward scattering of radio waves. The first radio activity peak was found at $04^{\rm h}10^{\rm m}$ UT and the secondary peak at $10^{\rm h}40^{\rm m}$–$11^{\rm h}00^{\rm m}$ UT.

Comparing two potential meteor cameras — the Mintron and the Watec 120N

Detlef Koschny

Recent developments coming from the security and surveillance sector resulted in new video cameras with very sensitive detectors, which make meteor observations without image intensifiers possible. This paper compares the image quality of two of these cameras, the Mintron and the Watec 120N.

The ESA Leonid campaign 2002 to Spain

Detlef Koschny, Roland Trautner, Joe Zender, André Knöfel, Jorge Díaz del Río, Rüdiger Jehn

We report on the *ESA* Leonid campaign in 2002. As in 1999, our team went to Southern Spain for double station observations around Granada. We mainly performed video observations; two of our cameras were equipped with objective gratings. We operated one video camera on board an airplane. The electric field of the Earth's atmosphere was also measured. This paper describes our setup and gives some very first results.

Meteor observation from space — The Smart Panoramical Optical Sensor (SPOSH)

Detlef Koschny, Mario Di Martino, Jürgen Oberst

The European Space Agency (ESA) is funding two parallel studies for a "Smart Panoramic Optical Head". The main goal is to develop the technology for a space-qualified, very light-sensitive camera with a wide field of view, both from the hardware and the software side. The scientific application is to allow imaging of phenomena on the dark side of planets or moons, e.g. lightning flashes from thunderstorms or electrical discharges in sand storms, meteors, impact flashes, aurorae, etc. This paper will concentrate on the potential of this camera for the study of meteors from an orbit around a planet.

Summer observations at the Astroclub "Canopus" 2003

Maria Krumova

Research into the characteristics of meteor showers from multi-frequency radio observations

Kayo Miyao and Hiroshi Ogawa

Observing meteor showers by several kinds of radio at different frequencies reveals some characteristics of a meteor shower. Different radio waves with different frequencies detect different range of altitude. As the result, different frequencies detect meteors of different magnitude ranges. Consequently, the approximate mass distribution of meteoroids can be estimated by the results of different frequency radio.

List of meteorites recorded in China

Nagatoshi Nogami

Based on “General Compilation of Ancient Chinese Astronomical records” (1988), and following research which utilized Chinese materials collected in public libraries in Japan, more than two hundreds meteorite falls recorded from 1019 to 1911 are listed. They consist of two categorized parts, one a group of events whose fall times have less than twenty-four hours error, and the others. Every event of the former category is described with its fall date in solar longitude at equinox 2000. And all events are listed with classification as stone or iron, character of shape, size, color and so on, sound, path direction and fall site in modern provinces. However, not all events have a description of all these items. Among these events a few interesting cases are mentioned such as topics of smell of the atmosphere at the fall, if dangerous for humankind, and ice meteorite.

Japanese Radio Meteor Observation Research Program

Hiroshi Ogawa

Radio Meteor Observation has recently become famous in Japan. However, it has serious problems. The typical problem is the reflection area over which it is possible to receive meteor signals of underdense echoes. In this work, the reflection area of radio meteor observation was simulated and the simulated area was compared with optical observations. As a simulation result, the reflection areas and optical observation results are shown visually; high coincidence rates were obtained. The reflection area must therefore be considered when discussing meteor flux distribution.

The international project for radio meteor observation 2001 – 2003

Hiroshi Ogawa, Shinji Toyomasu, Kouji Ohnishi, Kimio Maegawa, Shinobu Amikura, Kayo Miyao

There are about 150 radio meteor observing stations in the world. At the moment, worldwide data are combined by using relative value to monitor whole meteor activity without radiant and weather problems. This project was planned for major meteor showers since 2001. We have succeeded in monitoring and investigating several major meteor showers. Furthermore, this project has provided FLASH and LIVE contents. This international project therefore was not only useful in monitoring but also in providing the latest information. This research reports how to combine worldwide data, project organization and some results of the major meteor showers in 2001 and 2002.

The population index of sporadic meteors

Jürgen Rendtel

In this work we determine the population index r of sporadic meteors from visual meteor data. A sample of 301 499 meteor brightness estimates collected from 1196 observers in the period 1988 – 2003 and stored in the *IMO*'s visual meteor data base (VMDB) is used. Selection effects are discussed and annual as well as diurnal variations are discussed. Main results are derived from northern hemisphere data which comprise the major portion of the sample (278 724 meteors). The annual average value is $r = 2.95 \pm 0.06$. A minimum occurs in (northern) summer between 80° and 100° solar longitude (J2000) with $r = 2.80 \pm 0.05$, and a maximum is found between 200° and 220° solar longitude with $r = 3.10 \pm 0.05$. Similar variations occur in the respective seasons in the southern hemisphere.

International cooperation and amateur meteor work

Paul Roggemans

Today, the existing framework for international cooperation among amateur meteor workers offers numerous advantages. However, this is a rather recent situation. Meteor astronomy, although popular among amateurs, was the very last topic within astronomy to benefit from a truly international approach. Anyone attempting long term studies of, for instance, meteor stream structures will be confronted with the systematic lack of usable observations due to the absence of any standards in observing, recording and reporting, any archiving or publishing policy. Visual meteor observations represent the overall majority of amateur efforts, while photographic and radio observing were developed only in recent decades as technological specialties of rather few meteor observing teams.

The Geminid meteoroid stream: a new model

Galina O. Ryabova

A year ago, in Frombork, a method of mathematical modeling of the Geminid meteoroid stream formation was considered in detail (Ryabova, 2003). So here the main attention is focused on results of the modeling. The importance of comparative study of the Geminids and Daytime Arietids is discussed.

Observations of the 2003 Perseid meteor stream

Jaroslav Stehlik

The Starfriends project

Arnold Tukkers

What happened with π-Puppids in April 2003?

Jérémie Vaubaillon

The evolution of a short period meteoroid stream (π-Puppids) is investigated. It appears that Jupiter takes a preponderant role in its dynamics, because of close encounters that occur frequently. This study reveals that a meteor shower is possible even if the parent body is at aphelion, because of the extent of the stream. Predictions of the 2003 π-Puppids were made, but no observation confirmed the encounter. The very low entry velocity (18 km/s) and the very small particles involved in this prediction can explain why the shower was not observable.

Observations of the 2002 Leonids from Bulgaria

Valentin Velkov

The relationship between fireballs and HRO Long Echos

Erina Yanagida and Shinobu Amikura

Ham-band Radio Observation (HRO) is one of the major methods used to observe meteor activity in Japan. We receive certain types of meteor echoes. One of the types is the long-lasting echo called a "Long Echo". We have the impression that Long Echoes correspond to fireballs. The present research found this relation and tried to identify fireball data from visual observations with Long Echo data of the 2002 Leonids, Geminids, and Quadrantids. From these data, we found that the identification percentage tended to be higher for fainter magnitudes, but that the percentage is small, the percentages of each meteor stream being less than 30%. From these results, this research found that we could not simply say that brighter meteors were received as Long Echoes. It depends on the geocentric velocity of the meteor stream, with a possibility that Long Echoes correspond to darker as well as brighter fireballs.

Previous notice on ERS Synthetic Aperture Radar Imaging of Impact Craters

Joe Zender

Due to interest in terrestrial impact crater structures during the *International Meteor Conference 2003*, the author gave an ad-hoc previous notice on a special publication of the *European Space Agency* titled "ERS Synthetic Aperture Radar, Imaging of Impact Craters". The special publication will be issued at the end of 2003.

Video intensified camera setup of visual and meteor spectroscopy

Joe Zender, Detlef Koschny, Olivier Witasse, André Knöfel, Roland Trautner, Jorge Díaz del Río, Margaret Campbell-Brown

Meteor spectroscopy
Introduction to theory, setup and data analysis

Joe Zender, Olivier Witasse, Detlef Koschny, Margaret Campbell-Brown, Jorge Díaz del Río, Roland Trautner, André Knöfel

The reader is introduced to the theory of meteor spectroscopy using video equipment. Practical hints on the selection, usage and installation of the necessary instrumentation are presented. The required data analysis is briefly described with example images and spectra that the authors obtained during the Leonid storm in 2001. Meteor spectroscopy using video equipment is an attractive and affordable observation possibility for amateur observers.

Observations of the Quadrantid meteor shower in 2003

Zhelyo Zhelev

TV Observations of Meteors from the Aquarius Region in early August

Peter Zimnikoval

Single-station TV observations in Aquarius near the radiant of the Aquarid meteor complex were carried out during three nights from August 1 to August 5, 2003. The observations continued at other localities during the night of August 12/13. Individual radiants of single meteors from were calculated from angular velocities. The associations to active shower were analysed. The method and result are discussed.

Visual Leonids in 2002 at Vartovka, Slovakia

Peter Zimnikoval

Quadrantids

2003 EH_1 and the Quadrantid shower

Peter Jenniskens [1]

Photographic observations of the Quadrantid shower in 1995 by members of the Dutch Meteor Society showed little sign of the diffusion created by frequent close encounters with Jupiter. From this, I suspected that the parent was still among the meteoroids, difficult to observe because it may no longer be active. On March 6, the Lowell Observatory Near-Earth Object Survey first spotted this asteroid and since the orbit was refined significantly by other observers in the next 48 days, I now find it very close to that expected for the Quadrantid parent. The identification of a dust trail in the orbit of 2003 EH_1 (the Quadrantids) identifies this object as a (now likely extinct) comet nucleus that appears to be the remnant of a larger object that broke up about 500 years ago. Only a breakup can account for both the young age and the large amount of mass in the stream. Efforts to link the orbit of 2003 EH_1 to that of comet C/1490 Y1 await a better orbit for 2003 EH_1, but do not seem to exclude the possibility that this sighting was associated with that breakup.

Received 2003 December 23

1 Introduction

The Quadrantids (Sauval, 1997; Fisher, 1930) is our most intense shower with rates peaking at Zenith Hourly Rate = 130 meteors/hr. Until now, it has been the only major shower with no known parent body. It was long thought that the comet had moved away from the meteoroid stream. This idea came about when it was found (Hamid & Youssef, 1963; Williams et al., 1979; Hughes et al., 1979; Hughes et al., 1980) that the orbit rotates very rapidly due to numerous close encounters with Jupiter. About 1 500–4 000 years ago, the orbit was inclined by only 13° and the meteoroids approached the Sun to within 0.10 AU. Today, the orbits of Quadrantid meteoroids are at a steep angle of 71° and do not come closer than 0.78 AU to the Sun.

2 Locating the parent body

Based on this rapid evolution, Bruce McIntosh (1990) first suggested that the newly discovered comet 96P/Machholz (now with $q = 0.12$, $i = 60°$) has a sibling relationship with the Quadrantid shower. The comet was in an intermediate stage of this evolution and could be part of a larger complex of dust that includes the Daytime Arietid and southern Delta-Aquarid showers. It was later found that such a complex could be as old as about 5 400 years, or as young as 2 200 years (Jones & Jones, 1993). More recently, Iwan Williams and S.J. Collander-Brown (1998) concluded for the same reasons that asteroid 5496 (1973 NA) is a likely candidate (Table 1), more likely than 96P/Machholz and even more likely than comet C/1490 Y1 (see below).

The idea that the shower was evolved and old was based to a large extend on very poor observational data (mixed in with some much better results...). When observers of the Dutch Meteor Society, in a photographic campaign led by Hans Betlem and a multi-station video effort led by Marc de Lignie, finally had a clear night on January 3, a total of 36 were obtained that came out very similar, with a small dispersion in radiant positions and an interesting stratification in speed and position.

That was very surprising, because Jupiter is supposed to rapidly disperse such orbits in a more or less random manner. Each time Jupiter is near the aphelion of the shower, some meteoroids will be relatively severely affected. Over time, that results in a rapid broadening of the stream. Only if the age of the shower is very young may we expect to find the parent still among the meteoroids.

Based on the measured dispersions of meteoroid orbits, and compared with the dispersion found in the models by Iwan Williams and Zidian Wu (1993), I concluded that the stream was no older than about 500 years (Jenniskens et al., 1997). Because most of the meteoroids escaped being ejected altogether, I suspected that the comet would also survive those close encounters with Jupiter. I predicted that an asteroid-like object would be found among the meteoroids and provided an approximate orbit of this parent, assuming that the Quadrantids would trace its path (Table 1).

Unfortunately, I was not certain where along the orbit the comet was hiding (the guessed position, a return in 2002.7, based on high rates seen in the past turned out to be less than half a year off). The results were published (Jenniskens et al., 1997) and I periodically checked the orbits of newly discovered minor planets for a possible parent.

3 Asteroid 2003 EH_1

Patience paid off last March. Although this comet is on a very steep orbit and passes by the Earth very quickly because the perihelion is near the Earth's orbit (see Figure 1), the comet does on occasion cross the field of view of the many active automatic asteroid search programs. The return in 1997 was not very favorable, but the return of 2003 was better. It was the Lowell Observatory Near-Earth Object Survey — LONEOS telescope (Observer B.A. Skiff) that first detected the asteroid. The initially published orbit was very imprecise and unlike that of the Quadrantids, but other observers followed

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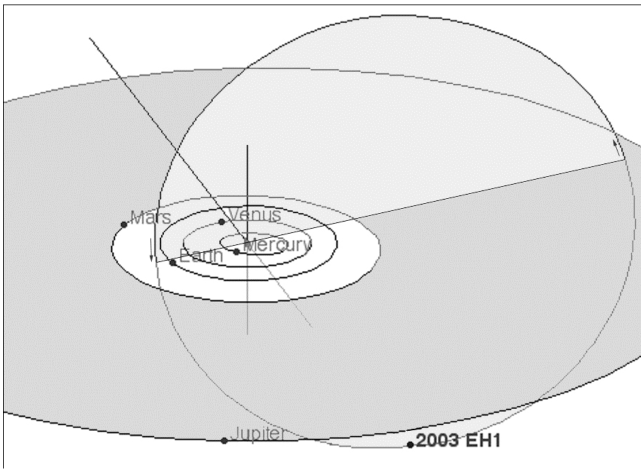

Figure 1 – Orbit and position of 2003 EH_1 in 2004 January 04.

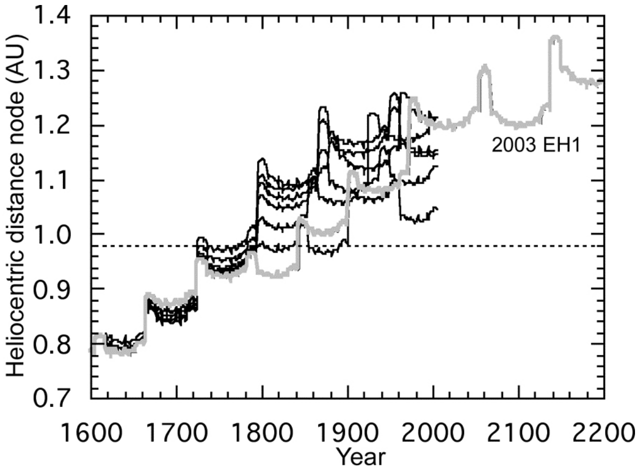

Figure 2 – Differential evolution of meteoroid orbits ejected from 2003 EH_1 in 1600 January relative to the evolution of the comet (gray line).

up and tracked the minor planet for 48 days (Marsden, 2003).

When I checked the asteroid database again recently, I found the updated orbit of minor planet 2003 EH_1 (meaning the 33rd object found during the period 2003 March 1-15) to be very close to the expected path of the Quadrantid parent body. Indeed, the theoretical radiant and speed for a shower from 2003 EH_1 (RA = 229.9°, DEC = +49.°6, Vg = 40.2 km/s at $\lambda_\odot$ = 282.9°; J2000) falls in the middle of those measured for the Quadrantids. The semi-major axis of 2003 EH_1 is exactly that measured for the Quadrantids, as are the inclination and argument of perihelion.

The node is a few tenths of a degree lower and the perihelion distance is significantly longer, now q = 1.19 AU while the Quadrantids have q = 0.98 AU. Indeed, the minimum distance between comet orbit and Earth (0.213 AU) is larger than typical for other annual showers (<0.04 AU).

To demonstrate that 2003 EH_1 is the Quadrantid parent, I calculated the orbit of the comet back in time, using the NASA/Horizons program, and found that the perihelion distance q changed the most rapidly and has moved outward in the last few hundred years. I tested only a few orbits, because the evolution has been studied in detail before, finding the same results (Hughes et al., 1981; Gonczi et al., 1992; Williams & Wu, 1993). The node has steadily declined at a gradual pace. A single perturbation of the parent body by Jupiter can move it significantly away from the stream center and that seems to have happened in a close encounter in 1972.

By ejecting particles with slightly wider orbits from the comet in 1600 (a random year, but set by the limit of the integration program used), I find that forward in time, the meteoroids spread in the expected manner relative to the position of the comet (Figure 2). The close encounters with Jupiter especially spread out the perihelion distances in a manner found before by Iwan Williams and Zidian Wu (1993).

The resulting shower is a ribbon, narrow in Earth's path, but wide in heliocentric direction. Based on the orbital evolution and the observed peak rates (McIntosh & Šimek, 1984; MacKenzie, 1980; Rendtel et al., 1993; Jenniskens, 1985), the spread in heliocentric direction can be measured. After taking that large dispersion into account, I find a total mass of about 1×10^{13} kg for grains in the range 10^{-9} kg to 1 kg (Jenniskens, 1994). That is about 300 times the amount of dust lost by comet 55P/Tempel-Tuttle in a single orbit. Hence, I suspect that the Quadrantid shower was created in a breakup of the parent comet about 500 years ago, from which 2003 EH_1 is a remnant (about 6×10^{12} kg in mass). More such remnants (presumably smaller) may be present among the Quadrantids (a potential impact danger).

4 C/1490 Y1

It is not necessary that this breakup was observed. When recent comet C/1999 S4 (LINEAR) broke apart into about 26 small fragments in 2000, it brightened only modestly. However, there happens to be a sighting of a comet C/1490 Y1 by Chinese, Korean and Japanese astronomers at about the right time for the proposed breakup 500 years ago. Ishiro Hasegawa (1979) first pointed out the similarity of the parabolic orbit calculated for C/1490 Y1 and the orbit of the Quadrantids. Iwan Williams and Zidian Wu (1993) investigated the case and found that a short period orbit would fit the observations as well. (They continued to propose that comet had a close encounter with Jupiter in 1650 and was ejected from the stream, and that the shower itself was 5 400 years old (Wu & Williams, 1992).)

Sadly, it turns out to be very difficult to tie the two objects together in a common orbit at this moment. 2003 EH_1 has too many close encounters in the backward integration. The calculations are very sensitive to even small changes in the initial orbit. Moreover, the initial orbit after the breakup could have been affected by the rocket effect of water vapor streaming away from the nucleus. Most solutions put the perihelion distance and inclination relatively low, which would cause the apparent orbit of the shower to shift lower in

Table 1 – Orbital elements of possible parent objects of the Quadrantid shower (J2000).

Object	T (UT)	q (AU)	e	a (AU)	ω (°)	Ω (°)	i (°)
Quadrantids (1) (2)		0.979	0.69	3.14	171.2	283.3	71.05+72.7 (3)
Variance		±0.002	±0.03	< 0.27	±2.1	±0.16	±1.0
2003 EH_1 (2)		1.1979	0.6176	3.1320	171.19	282.952	70.68
2003 EH_1 (2003)	2003 Feb 24.5	1.1924	0.6188	3.1277	171.368	282.938	70.798
Meteoroids ejected from 2003 EH_1 in 1600:							
(2)		1.157	0.628	3.114	173.38	283.08	71.24+72.4 (3)
Variance		±0.064	±0.020	±0.041	±1.20	±0.11	±0.56
Derived epoch of meteoroid ejection		-.-	~ 1400	-.-	~ 1300	~ 1420	~ 1290
C/1490 Y1 (4)	1491 Jan. 08.9	0.761	1.000	-.-	164.9	280.2	73.4
Not parents, but perhaps related:							
96P/Machholz	2002 Jan. 08.6	0.1241	0.9582	2.969	14.596	94.609	60.186
5496 (1973 NA)	2003 Sep. 28.0	0.8829	0.6373	2.435	118.124	101.109	68.003

Notes:
(1) See (Jenniskens et al., 1997).
(2) Epoch 1995 January 04.15, the moment the meteoroids would have been seen as meteors. These values are extrapolated.
(3) These double numbers represent two clusters of orbits that follow from the integrated orbits.
(4) See (Hasegawa, 1979).

the sky than suggested by the Chinese descriptions in 1491. One promising solution is shown in Figure 3. Indeed, several solutions were found that suggest there could be a common orbit. On request, Brian Marsden looked into this as well and confirmed that a common orbit might exist. A better result is expected when the orbit of 2003 EH_1 will be better known.

The identification of 2003 EH_1 as a remnant of the parent of the Quadrantid shower was announced on 2003 December 08 in an IAU Circular (Jenniskens, 2003) and a paper has been accepted for publication in the Astronomical Journal. All major showers now have a known parent body.

The identification of the Quadrantid parent is more than just a curiosity. NASA's Deep Impact mission is scheduled to visit comet 9P/Tempel 1 in July 2005 to probe the internal structure of that comet nucleus. The discovery of a cometary nucleus fragment in the orbit of a meteoroid stream makes it possible to investigate the mineralogical and morphological properties of cometary dust originating from much deeper inside a comet nucleus than is typically observed in meteor streams. Moreover, the identification of 2003 EH_1 as an extinct comet nucleus could provide a new target for future missions.

In the near future, the identification of the parent will lead to much improved meteoroid stream models and we expect to learn a lot about the breakup process by careful comparison with observations. For that reason, it is important to keep observing the Quadrantid shower in the years to come in order to measure if intensity variations and differences in the shower's peak time may be linked to perturbations by Jupiter.

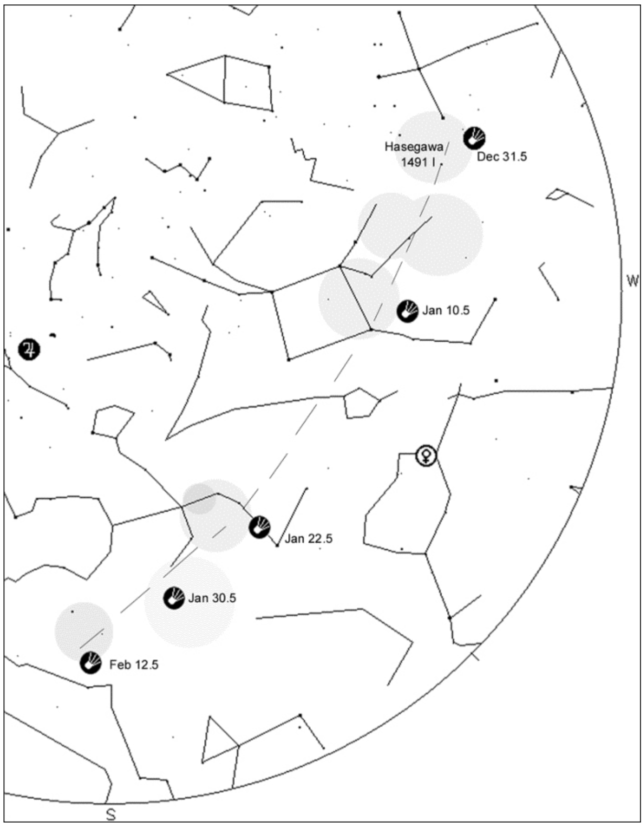

Figure 3 – Calculated position of the comet 1491 I for one possible common orbit with 2003 EH_1, compared to reported positions by Chinese, Korean and Japanese observers (gray circles, Kronk, 1999) and the best solution by Hasegawa (dashed line).

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Fundamentals of meteor science

Meteoroid streams: successes and problems

Iwan P. Williams [1]

There is general agreement that most of the annual Meteor Showers are caused by the interaction with the Earth's upper atmosphere of dust from Comets. The aim of this communication is to produce a general overview of what we know and agree upon while at the same time look at the problems that we still face. This should be taken as an encouraging sign, for when a subject is young or poorly understood, all emphasis is on the successes, but when the basic principles become well established, we can start highlighting the problems.

1 Introduction

Meteors are easily seen on any dark and clear night. It is not therefore surprising that records of the appearances of meteor showers go back for more than two thousand years. Indeed, Chinese observers record 'stars falling like rain' as early as March 687 BC, and these observations can be linked to the appearance of the April Lyrids (Hasegawa 1993). The change in appearance date from March to April is accounted for by the well known precession of the equinoxes. The fact that meteors have been observed for a long time does not however imply that the phenomenon has been subject to scientific investigation for a similar time interval. In fact, quite the reverse, for most of the observing interval it was simply a case of recording strange and unusual events which included comets and novae as well as meteor showers. The Chinese, Japanese and Koreans were particularly careful recorders and many of the records have survived to this day.

Greek philosophers had theories to explain most natural events and meteors were no exception. Aristotle suggested that they were atmospheric phenomena essentially similar in origin to lightning. Indeed the name 'meteors' comes from this connection with the same root as 'meteorology' for example. Others of course regarded meteor showers as portents of the end of the Earth. Unfortunately, such views are still held by some even to this day. By the Eighteenth Century, images of meteors were regularly appearing in paintings and sketches (see Olson and Pasachoff 1998, for an illustrated account of this) but there was still virtually no discussion of their true nature.

As with many other scientific developments, it is difficult to pinpoint exactly when things changed, but in 1800 Benzenberg and Brandes (1800) measured the parallax of over 20 meteors, concluding that they were on average at a height of about 90 kilometers. This value is close, but slightly less than the currently accepted mean value for the height of meteors. However, it is large enough to place meteors well above the conventional atmosphere of the Earth and so demonstrate that they are extra-terrestrial in origin. It is also not possible to precisely define when it was realized that many meteors occurred in showers, that is many more were seen on certain dates of the year. In many traditions, the Perseid shower, seen in early August, are referred to as 'The burning tears of St Lawrence' (Yeomans 1991).

Olmstead (1834) and Twining (1834) independently showed that meteors from what we now recognize as the Leonid shower appeared to emerge, or radiate out of a fixed point on the sky (located in the constellation of Leo), the obvious explanation for this being that the meteoroids responsible were moving on near parallel paths prior to intersecting the Earth's atmosphere. Herrick (1837) demonstrated the annual nature of the Perseid shower while Newton (1863, 1864, 1865) noted the comet-like orbits of individual meteors and that the annual showers would show periodicity on a sidereal rather than a tropical year. Though he was arguably not the first person to suggest that meteors were closely related to comets, Schiaparelli (1867) was the first to correctly identify a comet-meteor stream pair when he showed that the orbit of the Perseids was very similar to that of the newly discovered comet 109P/Swift-Tuttle.

Comet 3D/Biela is famous for having split into two easily identifiable fragments sometime shortly prior to 1845, subsequently disintegrating completely sometime after 1852. Strong meteor showers were seen in 1872, 1885, 1892 and 1899, dates when the Earth crossed Biela's orbit close to the point where the comet would have been. This was the final proof, if any were needed, of a connection between comets and meteor showers. Unfortunately it also led to two false trails, the first that meteor streams were formed through the disintegration of a comet and the second that comets were essentially formed of an aggregation of dust particles. Both of these notions made it difficult for researchers to find the correct model for meteor showers.

This situation changed in 1950 when Whipple (1950) proposed his, now well-known, icy conglomerate model for comets. In this model, there exist a single comet nucleus that is composed of an icy matrix within which dust grains are trapped. As the comet approaches the Sun, solar radiation causes the nucleus to heat up. At a heliocentric distance of a few astronomical units, the temperature is high enough for the ice to start subliming. As the comet approaches closer, so this sublimation increases, reaching its maximum in the general neighbourhood of perihelion. The outflow of gas caused by this sublimation will carry with it the imbedded grains

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proved the gas drag can overcome the gravitational field of the nucleus.

Whipple (1951) also proposed a mathematical model to represent the physical process described above and obtained a formula giving the ejection speed, V of the meteoroids relative to the cometary nucleus at a heliocentric distance r (in astronomical units) as

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

where σ is the bulk density of the meteoroid and b is the radius of the meteoroid in cm. R_C is in kilometers and all other quantities in cgs units.

As we can see, on this model smaller and less dense meteoroids achieve a higher speed than large meteoroids and very large meteoroids (larger than about 10 cm) would not be able to escape. It is also clear, by substituting typical values into the above formula that V at a few tens of meters per second is very much less than the orbital speed of comets a few tens of kilometers per second. Thus when the meteoroids escape from the comet, both their energy and angular momentum in a heliocentric frame are very similar to those of the parent comet. In other words the orbit of the grains, as free particles, will be essentially similar to that of the comet and a stream of meteoroids has been formed.

Following formation, the motion of the meteoroids gets modified by various effects, primarily those of radiation pressure and gravitational perturbations from the planets, so that the stream evolves after formation. Radiation pressure is in reality an outward force on the meteoroid, thus there is in reality an asymmetry about meteor streams in relation to the parent comet, more will be outside and behind the comet. Much of the more recent investigations have been concerned with this evolution.

Finally, if the meteoroid collides with the Earth's atmosphere, it will ablate and can be observed from the ground or detected through the reflection of radio waves. As can be gathered from the above discussion, the only way of connecting an observed meteor with its origin is through a similarity in the orbit, it is thus very important that observations of meteors do determine the meteoroid orbit. To do this, both the position and the velocity of the meteor are required. The angular velocity of a meteoroid can be determined from the time taken to cover the visible trail, so that with the height determined, both velocity and position became known, enough information to calculate the Keplerian orbit. Without some permanent record, determining the time taken for the meteor to cover a given distance was more a matter of guessing than real measuring. In time photography became possible so that the trail length can now be easily measured. However, the time taken is still undetermined, it could be any quantity smaller than the exposure time. To overcome this problem, two new devices were produced, the rotating shutter and the rocking mirror. In the first, an obstruction rotates at a known rate in front of the camera lens, in effect blocking off the light from the photographic plate at given time intervals. This leads to the trail on the photograph having a series of breaks in it, with the time interval between breaks known. In the second, the mirror which reflects light into the camera oscillates, or rocks, at a known rate, causing the light to fall on slightly different parts of the photographic plate and leading to a wave-like trail rather than a straight one, with the time interval between given points on the wave being known. The first method is still in use today, though with video equipment and charge coupled devices (CCDs) replacing the photographic plate. The principle however remains the same, the time taken to cover a specific distance is obtained. In 1895 Weinek (1886) obtained the first ever photograph of a meteor, though unfortunately his attempt to obtain multi-station photography failed. Photographic work on meteors was also carried out by Elkin (1899) and he obtained the first accurate determination of meteor velocities (Elkin, 1900).

The work described so far addresses visual observations, but only the larger meteoroids produce a trail that is bright enough to be seen.

Early work on radio transmission by Appleton & Barnett (1925), Breit & Tuve (1925, 1926) established the existence of a conducting ionized layer in the upper atmosphere. Appleton (1930) discovered that there was a sudden increase in the ionization during the night, concluding that 'there was some agent present which can influence the dark side of the Earth'. Nagaoka (1929) had suggested that meteors could affect the propagation of radio waves, but this idea seems not to have received much attention at the time. These changes in the ionization level of the ionosphere were causing serious problems for radio communications. One school of thought suggested that cosmic rays were affecting the ionosphere, hence causing the problem. Skellett (1931, 1932, 1935) (apparently ignorant of Nagaoka's work) independently suggested instead that meteors might be the culprits. In a paper immediately following Skellet's second paper referred to above, Schafer & Goodall (1932) had found very disturbed conditions in the ionosphere during the Leonid shower of 1931. At about the same time Jansky had developed a rotating aerial in order to try to locate the source of static noise in transmissions, which was eventually shown to be from a source near the center of the Milky Way. Perhaps because of this, little seems to have been done for a number of years to either verify or disprove Skellett's suggestion that meteors were the culprits.

On February 12th 1942, an incident took place which had no direct bearing whatsoever on our meteor story, namely the sailing of the two warships, Scharnhorst and Gneisenau from Brest to Germany undetected by the British Navy. Books have been written about the incident and how it was achieved, but this communication is not the place to investigate this interesting story. The British Costal radar system had however been jammed throughout the incident and in consequence The Army Operational Research Group was order to give top priority to solving this problem of radar jamming and Hey was assigned to this work. In a then secret report, Hey (1942) concluded that the jamming was in fact caused by solar outbursts rather than through any action on the part of the German military. It is another case where radars were apparently being jammed that is relevant to the development of the meteor story. In 1944, Hey was involved in modifying the anti-aircraft radar system so that they could detect V2 rockets in the hope that a few minutes warning could be given to the civilian population. A major problem encountered was the existence of a large number of transient radar echoes, resulting in many false alarms. Hey and Stewart (1946) proved that these transient echoes were from meteor trails because of the increase in echoes during the Quadrantid shower in January and the Lyrid shower in April. Final proof of the correctness of this meteor hypothesis came with the Giacobinid meteor storm of 1946, when 10 000 echoes per hour were recorded instead of the usual 2 or so (Hey *et al.* 1947; Lovell *et al.* 1947). Hey & Stewart (1947) also identified the echo as being the 'head echo', that is specular reflection of the radio wave off the head of the meteor, which could be used to obtain the speed of the meteor by the application of simple geometric principles. McKinley & Millman (1949) showed that individual meteor orbits could be determined using head-echoes provided three stations were used. At about the same time, Appleton & Naismith (1947) found that the wavelength of the returning echo was changed, and concluded that this was due to the Doppler Effect which provided a further method to determine meteor velocities.

Herlofson (1946) had suggested that the ionized trail behind a meteor should, in theory, produce the well known Fresnel diffraction pattern. This pattern was successfully observed by Ellyet & Davies (1948) who proceeded to measure velocities of daytime meteor showers (Ellyett, 1949), their existence having been demonstrated by Clegg *et al.* (1947).

2 The Current View of Meteoroid Streams

Over the last two decades there have been many changes in our view of the Solar system in general and many of these affect our views of the meteor story. There have been numerous fly-by missions to comets, while computing power has increased phenomenally. Nevertheless, the changes to meteor stream science have been more in the detail than in the actual basic model. We still believe that they are formed through meteoroid ejection from cometary nuclei, that they experience some orbital changes due to radiation pressure and planetary perturbations and that they become observable through ablation in the Earth's atmosphere.

The physics of the formation of meteoroid streams is very straightforward and non-controversial. As the cometary nucleus approaches the Sun, it heats up until a stage is reached where some of the ices sublime and become gaseous. The heliocentric distance at which this occurs will depend on a number of parameters, the composition, the albedo and the rotation rate for example, but the process which follows this is independent of these details. When sublimation occurs, the gaseous material flows outwards away from the nucleus at a speed which is comparable to the mean thermal velocity of the gas molecules.

Conservation of mass must apply to this gas flow so that $\dot{M}$, the mass outflow rate, is given by

$$\dot{M} = \alpha R^2 \rho W, \tag{2}$$

where R is the distance from the nucleus center, ρ the gas density, W the gas outflow speed, which we take to be the mean thermal velocity and α the solid angle into which the gas flows. For a homogeneous axi-symmetric flow, α will be equal to 4π, while for flow out of a number of discrete vent it will be the sum all over such active outflows.

Meteoroids are carried outwards, accelerated by gas drag. An expression for gas drag valid for all speeds was derived by Baines *et al.* (1965) and this reduces for the case when the relative speed is less than the mean thermal velocity of the molecules to

$$F_D = Kb^2 \rho v W, \tag{3}$$

where K is a constant whose value depends on the way gas molecules are reflected off the meteoroid surface but will generally be close to, but slightly larger than, π and b is the radius of the meteoroid.

Eliminating ρ between these two expressions gives

$$F_D = \frac{Kb^2 v \dot{M}}{\alpha R^2} \tag{4}$$

where v is the relative speed. The outward motion of the meteoroid will be opposed by the gravitational field of the comet nucleus, that is, by a force F_G given by

$$F_G = GM_C M_m R^{-2}, \tag{5}$$

where M_C is the mass of the comet nucleus, M_m the mass of the meteoroid and G the universal gravitational constant.

A meteoroid will escape from the cometary nucleus and be ejected into inter-planetary space provided $F_D > F_G$. This reduces to

$$\frac{M_m}{b^2} < \frac{Kv\dot{M}}{\alpha G M_C}. \tag{6}$$

Since M_m is proportional to b^3, this inequality is equivalent to stating that for a given comet, there is a maximum size of meteoroid that can escape.

The equation of motion of such an escaping meteoroid is given by

$$M_m \ddot{R} = F_D - F_G. \tag{7}$$

If it is assumed that the meteoroid speed does not get accelerated up to the outward flow speed of the gas, then the relative speed v is almost the same as W, the gas speed. In this case equation (7) can easily be integrated to give

$$\dot{R}^2 = \frac{2}{R_C}\left[\frac{C\dot{M}Wb^2}{M_m} - GM_C\right], \qquad (8)$$

where R_C is the radius of the nucleus, and C a constant. For a well-observed comet, with a nucleus of known dimensions, numerical values can be directly inserted into equation (8). For comet 1/P Halley for example with a gas production rate close to perihelion of the order of 10^{29} mol s^{-1} and a nucleus with a radius of 10 km, a millimeter sized meteoroid would have an ejection speed of the order of 50 ms^{-1}. This is not a very useful way of proceeding since the gas production rate will vary with heliocentric distance and the ejection velocity will have to be evaluated at each point of the orbit based on known values. A number of authors have attempted to obtain a more general formula by making assumptions about some of the parameters in the above equation. This is what Whipple (1951) did in order to obtain the formula given earlier.

A significant assumption in the above discussion is that the meteoroid is spherical. In many situations, this will not be true and Gustafson (1989) investigated modification due to non-sphericity. This however makes the problem much harder and, in this broad-brush approach, we will continue with this assumption. A second assumption is that the gas flows outwards in a simple manner with a speed similar to the thermal velocity. This may also not be true, Harris and Hughes (1995) arguing that it in effect accelerates into vacuo, and this has an effective speed much higher that assumed above. Crifo (1995) took a kinetic approach to the gas flow, arriving at another variation. The most recent investigation is by Ma *et al.* (2002). Finson and Probstein (1968) produced a model for dust outflow that related the observed brightness variations along the cometary tail to the dust flow rate. All, with the exception of Harris and Hughes, predict meteoroid velocities relative to the nucleus of the order of tens of meters per second.

Let us consider the **maximum** changes that can be brought about between the orbit of the meteoroid and that of the comet. The maximum energy change takes place when the meteoroid is ejected along the direction of motion of the comet and this also corresponds to the maximum change in specific angular momentum. Call the orbital speed V and the meteoroid speed of ejection v_m, then the change in specific energy, E, is given by

$$2\Delta E = (V + v_m)^2 - V^2, \qquad (9)$$

and, since v_m is much less than V, this gives

$$\Delta E = V v_m. \qquad (10)$$

Now, standard theory of Keplerian motion tells us that

$$E = \frac{-GM_\odot}{2a}, \qquad (11)$$

where a is the semi-major axis of the orbit in Astronomical Units. Hence we can obtain

$$\frac{\Delta E}{E} = \frac{-\Delta a}{a}. \qquad (12)$$

The maximum change in a occurs when V is largest, namely at perihelion, so that

$$\frac{\Delta a}{a} = \frac{2(1+e)}{(1-e)}\frac{v_m}{V}. \qquad (13)$$

Hence, unless the eccentricity e is very close to unity, the changes in a are of the order of the ratio of ejection to orbital speeds. Working to the same order, $V\Delta h = v_m h$, and using the standard expression for h,the angular momentum per unit mass, we obtain

$$\frac{\Delta e}{(1+e)} = \frac{2v_m}{V}. \qquad (14)$$

Since the ejection of the meteoroid was assumed to take place at perihelion and in the orbital plane, in this model there will be no change in the inclination, i, the longitude of the nodes, Ω, or the argument of perihelion, ω. There will however be a change in the nodal distance, r_N. The maximum change occurs when perihelion is equidistant between the two nodes and in this case, simple arithmetic gives

$$\frac{\Delta r_N}{r_N} = \frac{2\Delta v_m}{V}. \qquad (15)$$

So far, we have only considered ejection in the plane of the orbit of the parent comet, which leaves the orbital plane of the ejected meteoroids also as this plane. Since the plane of the orbit determines the longitude of the nodes and this angle is easy to determine from observations (being essentially the time at which the meteors are seen) any changes to this plane may be important. This problem was investigated fully by Ma & Williams (2001) and the results are also given in Williams (2002).

$$\Delta\Omega = \frac{\tan\Delta i}{\sin i}, \qquad (16)$$

and from considerations of momentum,

$$\tan\Delta i = \frac{v_m}{V}. \qquad (17)$$

If we do not assume that ejection occurred at perihelion, the expressions get more complicated but can be found for example in Williams (2002). In essence, however, the situation is unchanged, if the ejection velocity and location are known, then the orbital parameters of the ejected meteoroid can be determined, and, since $P^2 \propto a^3$, this includes the period. The importance of the period, as was first pointed out by Wu and Williams (1996) is that if a meteoroid was ejected at a known date and observed at another known date, then the period of the meteoroid is known, which leads through the above equations to the ejection circumstances being known. This principle, applied slightly differently, was used very successfully by Asher *et al.*. (1999) to explain and predict the time of the occurrence of storms in the Leonid shower over recent years.

There is one further effect that needs to be considered in connection with the formation process and that is the effect of solar radiation. Radiation exerts a radially outward force on all bodies which is proportional to the cross-sectional area of the body. Since gravity is proportional to the mass, it is clear that for small bodies the effect of radiation may become important. Solar radiation falling directly on a body generates a force which is radial and depends on the strength of the incident radiation and so is proportional to the inverse square of heliocentric distance, like gravity. It can thus be regarded as weakening gravity and is usually represented by writing the effective force acting on the body as

$$F = -\frac{GM_\odot(1-\beta)}{r^2}, \tag{18}$$

and β is given by (see for example Burns *et al.* 1979)

$$\beta = \frac{5.75\times 10^{-5}}{b\sigma}, \tag{19}$$

where as before b is the meteoroid radius in centimeters and σ the relative bulk density in $\mathrm{g\,cm^{-3}}$. It is self-evident that meteoroids will be lost from the Solar System if $\beta \geq 1$, since the net force is then outwards. However, as Kresák (1976) first pointed out, meteoroids will be lost whenever their total energy is positive. A meteoroid moving with the parent comet will have a specific energy E' given by

$$2E' = V^2 - \frac{2GM_\odot(1-\beta)}{r}. \tag{20}$$

But,

$$V^2 = GM_\odot\left(\frac{2}{r}-\frac{1}{a}\right), \tag{21}$$

so that E' is positive provided

$$2\beta \geq r/a \tag{22}$$

At perihelion, $r = a(1-e)$, and here, meteoroids for which

$$\beta \geq (1-e)/2 \tag{23}$$

will be lost. This is a much more restrictive limit than $\beta = 1$, so that larger grains are lost than is implied by the $\beta = 1$ limit. Taking our numerical example again, for comet 1P/Halley, $e = 0.964$, so that meteoroids for which $\beta \geq 0.018$ will be lost. Taking a bulk density of $0.5\ \mathrm{g\,cm^{-3}}$, meteoroids smaller than about 6×10^{-3} cm will be lost from the stream.

It is also important to remember that meteoroids will, in general, be ejected on every occasion that the parent comet is close to perihelion and that the initial spread in orbital parameters caused by the ejection process will be about the cometary orbit at that instant in time.

2.1 The Evolution of Meteoroid Orbits

Once the meteoroid is free of the cometary out-gassing process, it moves as an independent body in the Solar System and so its motion is dominated by Solar gravity, in other words it moves on an elliptical orbit as we have already stated. Solar gravity may be weakened through the effect of radiation pressure, but the dominant force is still inverse square and so the orbit is still basically elliptical. Like other bodies in the Solar System, the motion of the meteoroid will be affected by the gravitational fields of all the other bodies in the system, with all the accompanying problems of accurately dealing with these perturbations that are familiar to all that have worked on orbital evolution in the Solar System. It is known since the work of Poincaré in 1892, (see Poincaré 1957) that no analytical solution exists to the general problem of following the orbital evolution of bodies in the Solar System. Hence, following the motion of meteoroids implies some form of numerical integration of the equations of motion.

In addition to gravitational perturbations, the motion of the meteoroid, as already mentioned, will be affected by the Poynting-Robertson effect and possibly the Yarkovsky effect. Since even the largest meteoroids are quite small in mass, their rotation is affected by even single photons striking them. Hence, their rotation is generally considered to be random and variable on a short time-scale. For this reason, the cumulative effect of the Yarkovsky phenomenon is regarded as being small and has generally been ignored. The Poynting-Robertson effect has been studied by many authors. The first to apply this to meteoroid streams were probably Wyatt and Whipple (1950). More recent accounts of this effect can be found in Hughes *et al.* (1981) and Arter and Williams (1997). It is fundamentally a process for removing angular momentum from the meteoroid and so leads to a reduction in both semi-major axis a and eccentricity e with time. In writing equations for these changes, it is more convenient to use a parameter η, rather than β, to characterize the effects of radiation. The relationship between the two parameters is

$$c\eta = GM_\odot\beta, \tag{24}$$

where c is the speed of light. Hence, η has a numerical value 4.4×10^{15} that of β in *cgs* units. Note that while β is dimensionless, η is not. Using this notation, all the authors mentioned give the following two equations, (using the same units as those used to express η)

$$\frac{da}{dt} = \frac{-\eta(2+3e^2)}{a(1-e^2)^{3/2}}, \tag{25}$$

and

$$\frac{de}{dt} = \frac{-5\eta e}{2a^2(1-e^2)^{1/2}}. \tag{26}$$

In order to obtain the change in a given orbit, it is necessary to specify the dimensions of the meteoroid so that the value of η can be obtained and then numerically integrate these equations, the latter task not being particularly difficult. For the case we have so far used as an example, namely a meteoroid of 1 mm radius and density $0.5\ \mathrm{g\,cm^{-3}}$ associated with comet 1P/Halley, this time-scale for a significant orbital change is of order 3×10^5 years. Though this is short by the standards of evolution generally in the solar system, it is a long time compared to our time-span of observation of meteor showers and is towards the top end of estimates for stream life-times. The time to significantly change the orbital parameters will also vary from stream to stream, so that the above value should be regarded as only an indication of the time scale for the Poynting-Robertson drag to be important. For many investigations, it may be justifiable to leave out considerations of the Poynting-Robertson effect, though in fact since the investigations of planetary perturbations has to be numerical, the effect can be included in the equations of motion at virtually no extra computing costs.

The concepts involved in considering planetary perturbations are very easy to understand though following through the consequences is somewhat harder. Each planet produces a gravitational field whose value is given by the usual inverse square law of Newton. Hence, if the position and velocity of each body in the system is known at any given instant, then the force field can be evaluated for each body and its instantaneous acceleration calculated. This is of course exactly the same problem as that faced by orbital calculators for comets, except that there are rather more meteoroids to be followed. In the mid-nineteenth century, this was a very active field though 'computers' had a rather different meaning then from now. In those days it meant a low-paid assistant who computed myriad of positions using hand calculators. Some of the earliest calculations on the evolution of meteoroid streams were by Newton (1863, 1864, 1865) who included planetary perturbations in his investigations of Leonid meteor storms. A number of other early calculations are described by Lovell (1954).

These methods were in essence the same as those used today in direct integration methods only with electronic computers replacing the human ones previously used. As computer hardware improved, the use of direct methods became more widespread. By direct methods, we mean any method where the equations of motion of individual meteoroids are integrated and the behavior of the stream deduced from the collective behavior of the individual meteoroids.

The first such investigation was probably by Hamid and Youssef (1963) who integrated the orbits of six actual Quadrantid meteoroids, deducing that drastic changes in the orbital elements were taking place in time-scales of a few thousand years, a result that was to be confirmed several times later for the Quadrantids. Sherbaum (1970) generated a computer program to numerically integrate the equations of motion using Cowell's method. This program was used by Levin *et al.* (1972) to show that Jovian perturbations caused an increase in the width of meteoroid streams. In the same year, Kazimirchak-Polonskaya *et al.* (1972) integrated the motion of 10 α-Virginid and 5 α-Capricornid meteoroids over a 100 year interval. Seven years later, the number of meteoroids integrated was still small and the time interval over which the integration was performed remained short, Hughes *et al.* (1979) integrating the motion of 10 Quadrantid meteoroids over an interval of 200 years, using the self adjusting step-length Runge-Kutta method. This however marked the start of significant increases in both the number of meteoroids integrated and the total integration time. By 1983, Fox *et al.* were using 500 000 meteoroids, indicating that in five 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 (1982, 1986), Wu and 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 and Williams (1993) for example. 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, numerical integrations of models for all the major streams have been carried out.

2.2 Observations of Meteor Showers

As mentioned in the introduction, a meteor is a streak of light visible in the night sky as the meteoroid burns in the upper atmosphere due to friction. The heating is sufficiently high to allow the trail to be ionized. 'Observations' of this event can take many forms, a simple naked eye view of the streak of light, a television or video image of the same event, a photographic record or a CCD image are all forms of recording the visible phenomenon. Meteors can also be recorded through the radio reflection off the ion trail and the head. Radar can be used in either forward or backward scattered mode.

The first obvious quantity that can be obtained is the rate of influx of meteoroids, that is the number per hour say. This allows an activity profile to be drawn and from this both the time of maximum activity and the duration of the activity can be obtained. Corrections have to be applied to standardize these results and Meteor Observers have defined a quantity called 'The Zenithal Hourly Rate', this being the number of meteors that would be seen in an hour under ideal observing conditions if the radiant were exactly at the zenith. The rules for calculating this quantity are well established, but it must be remembered that the end result in terms of a published activity profile may be an order of magnitude greater than the original raw data.

Again as mentioned in the introduction, showers have identifiable radiant points. The location of this point is a function of the relative velocity of the Earth and Stream or, since the velocity of the Earth is known, it is in effect a function of the stream velocity (not speed, but a vector quantity with three components). Since the position of the radiant only has two degrees of freedom, this ALONE can not give the velocity of the impacting meteoroid, only the two components orthogonal to the radius vector in a geocentric reference frame.

In addition to the above, the angular speed of the meteoroid through the atmosphere can be obtained, for example by using a camera with a rotating shutter. If observations from dual locations are available then this can be converted to a speed, so that both position and velocity are now known and, in principle, a full determination of the orbital parameters is possible. Unfortunately it is still not common practice to use multiple locations when observing meteors so that the number of meteors with determined orbits is far less that the total number observed. The brightness of the meteor can also be determined, especially if video, photographic or CCD observations are made, which allows the cross-section to be determined. From the deceleration (change in speed) and the cross section, the density can be obtained. Instructions for reducing observational data were published as early as 1922 (Öpik 1922). Further details are in Koschack and Hawkes (1995).

If it is assumed that the meteoroid remains as a single solid sphere, then the simple physical considerations mentioned above in terms of energy and momentum will give the correct unique solution. This was investigated by Öpik (1922), Hoppe (1937) and Levin (1961) for example. This can easily be modified to take account of the energy required to cause ionization (Kaiser 1953, 1955). However, meteoroids may fragment. The process of fragmentation and the related physics was discussed by by Cook (1954) and Jacchia (1955). If a meteor fragments, then it increases its total surface area but preserves total mass. It thus behaves like a single body of lower density, and the actual density of the original body is higher than the derived density. Babadzhanov (1993) for example finds that under the fragmentation assumption, the density should be increased by a factor of around 10 over those found by Verniani (1969, 1973). In fact, the situation is even more complex, for the end correction to be applied depends on whether the fragmentation process is continuous or whether fragmentation is sudden at one instant of time.

Clearly, if a spectrum of a meteor can be obtained, then very important results concerning the composition of the original meteoroid can be deduced. The main difficulty in obtaining spectra is obvious, getting the meteor within the slit of the spectrograph. By definition, a spectrograph distributes the available photons over a wide range of wavelengths so that only a small fraction of the available total falls within a particular wavelength range. To obtain a particular signal to noise ration in a given range, one must either only measure very bright meteors or use very large telescopes. Hence, there is a very strong bias towards obtaining spectra of well known meteor showers such as the Leonids and the Perseids. Many spectra were obtained by Millman (see for example Millman and Halliday 1961, Millman *et al.* 1971) but not many have been published. The analysis is also model dependent and has been discussed by Borovička (1993). A very valuable contribution that such a study can make is however to identify species not hitherto suspected of being present, for example, Borovička and Zamorano (1995) found lithium in a fireball spectrum observed on 1988 December 18/19.

3 What needs to be done

It is fair to say that we now have a fair understanding of the general behaviour of meteoroid streams and the resulting meteor showers. That does not however mean that there is nothing to be done. Let me first highlight what I regard as outstanding problems. One of the most curious problems at present comes from the apparent differences in velocity profiles obtained by conventional radars and the large aperture radio telescopes (e.g. Arecibo and EISCAT). There are two aspects, the mean velocity is higher and also the the percentage of hyperbolic meteors observed is higher (this also includes AMOR) (see for example Williams 2004). Most of the observed meteors are in the sporadic background, and in particular the hyperbolic ones. Of course, large aperture radio telescopes are essentially the preserve of professional astronomers, but it may be interesting to also obtain more new observations in the visible of the sporadic background to obtain the velocity distribution.

The second major problem concerns meteoroid densities with a factor of the order of 5 between the derived densities of Babadzhanov and Verniani, arising mainly from the assumption of whether the meteoroid fragments or not. There is I suspect strong observational bias in the results, with decelerations for the brightest meteors being far easier to obtain. With CCD observations both deceleration and brightness variations are deducible and it would be valuable to get more information in this area.

The composition of meteoroid is also a matter of some importance. In the cometary nucleus, it is clear that some ices may be present within grains. Whether or not these evaporate before Earth encounter depends on the ice composition and also on the albedo, shape and dimensions of the meteoroid. Pellinen-Wannberg *et al.* (2004) claim to have discovered a water signature in Leonid observations. Knowing whether there is water in meteoroids is important for a number of reasons and so more spectral information to investigate this are needed. Unfortunately water lines tend not to be in the visible and are hard to observe. However, detection of OH would also be worthwhile.

Modelers tend to assume (for perfectly valid reasons) that meteoroids are predominantly ejected close to the perihelion point of the parent comet. It is certainly true that cometary activity is at its highest around perihelion, but it is possible that the larger grains are preferentially ejected when a vent on the nucleus first comes active. It may thus be instructive to look at situations where the larger visible meteors were ejected at a slightly different epoch from smaller ones.

The above is a wish list of interesting and slightly unusual things to do. Of course there is also much that can be done that is more main-stream. Any spectral information is valuable as is any data on the orbits of meteors. The ratio of meteors recorded to those that have a determined orbit is still very small.

What ever it is that you decide to do, enjoy it!

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Radio observations

First results of radio observations by CMW: the 2003 Perseids

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The first results of radio meteor observations made by the Polish Comets and Meteors Workshop (CMW) using the forward scatter technique are presented. Full coverage of the 2003 Perseid maximum showed a peak around $\lambda_\odot = 139.^\circ 87$.

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1 Introduction

The aim of forward scatter radio observations is the recording of meteor phenomena by receiving the signal of a distant radio station (about 500 – 2000 km from the receiver). Normally it is impossible to receive it directly due to the curvature of the Earth. When meteoroid matter burns it ionizes the surrounding atmosphere. This allows it to reflect the signal from the radio station (at a frequency in the range 40–180 MHz) so it can be detected by the receiver. The first long-term CMW observations using forward scatter were made during the 2003 Perseid maximum at Rybnik Kamień ($\varphi = 18°36'$ E, $\delta = 50°08'$ N).

2 Equipment description

We decided to make observations in the VHF sound broadcast band (87.5–108 MHz) using a 3-element Yagi antenna connected by co-axial cable a to car digital tuner. The antenna and receiver were situated far away from each other to avoid interference. An eight-bit analogue-to-digital converter (ADC) was made by ourselves to feed the computer with the radio signal. We used a Pentium 200 MHz, 16 MB RAM computer with about 500 MB of hard disk space. This can be seen in Figure 1.

In our first attempt at forward scatter we decided to make only counting observations. We used free software METEOR V8.2 A written by Pierre Terrier and available via the Internet (`http://radio.meteor.free.fr`).

3 Results of 2003 Perseid peak observations

The equipment preparations were finished a day before main Perseid peak. First we had to find an appropriate frequency to detect meteor signals. We found a free channel at about 103.3 MHz, with the antenna directed south, at which we could detect meteor phenomena but with no direct reception of any radio station from the Czech Republic.

We started our observations on 2003 August 12 at 20:00 UT and covered the whole Perseid maximum. Continuous observations were continued until August 21 to reduce daily variations in meteor activity (see Figure 2). We corrected the Perseid peak using those data and took into account the radiant elevation using the formula given by (Ogawa, 2002) (Figure 3).

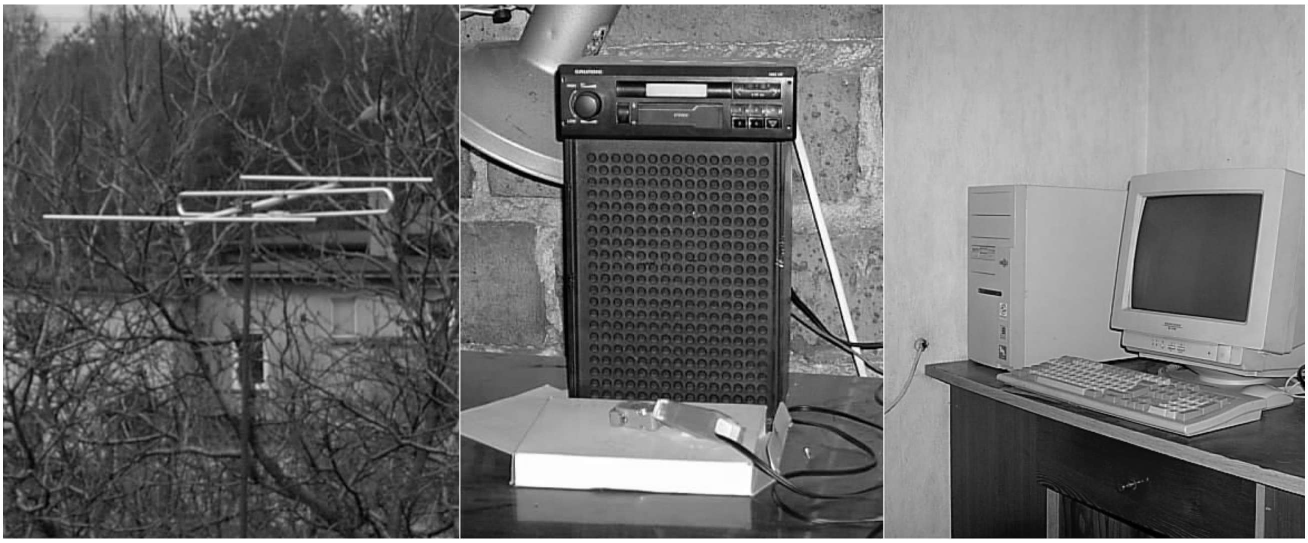

Figure 1 – Equipment used, left to right: antenna, receiver with ADC below and computer.

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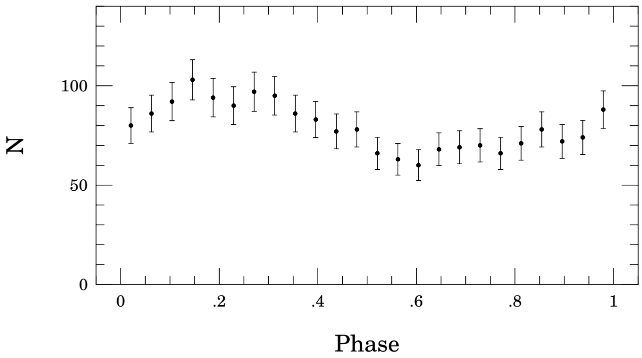

Figure 2 – Average number N of meteor echoes throughout the day, observed between 2003 August 13 and 21. Phases 0.0 and 1.0 correspond to 00^h00^m UT, 0.5 to 12^h00^m UT.

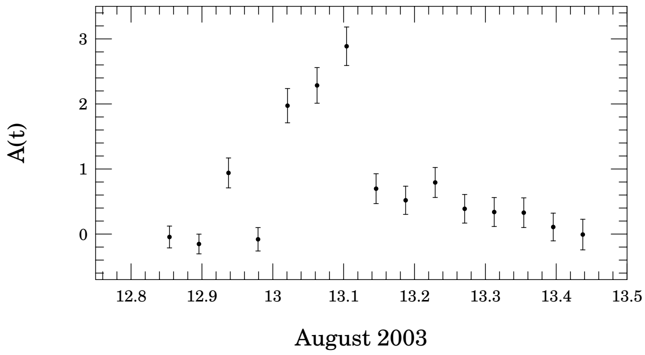

Figure 3 – Radio activity function $\mathbf{A(t)}$ during the Perseid maximum.

Esko Lyytinen predicted that the 2003 Perseid peak would be between $\lambda_\odot = 139\overset{\circ}{.}81$ and $139\overset{\circ}{.}82$ (`http://groups.yahoo.com/group/imo-news/message/1202`). We detected higher activity at $\lambda_\odot = 139\overset{\circ}{.}87 \pm 0\overset{\circ}{.}04$, which is about 1.5 hours after the predictions.

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Ongoing meteor work

Meteor trains and velocities: a pilot study

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A formula for the percentage of meteor trains in relation to meteoroid stream velocity is provided (assuming a power function), based on 2682 stream meteors observed by one visual observer.

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1 Introduction

Meteor trains are a blind spot for theoreticians on the one hand and many observers on the other. Train data is not stored in the Visual Meteor Database (VMDB), and a large fraction of visual observers do not note trains at all. However, there were and are attempts to gather and use train data (Vints, 1991; Verbert & Deconinck, 2001; Verbert, 2002) in a systematic manner. The actual IMO form for reporting meteor trains can be found in (Verbert & Deconinck, 2001). Observations may be sent to jver@urania.be . Verbert (2002) gives some aims of this research topic:

1. to establish relationships between meteor brightness and velocity and train formation
2. to establish relationships between chemical composition of meteoroids and train formation
3. to find variations in train formation (seasonal or with solar cycle)

A further idea connected with (3) is given in the discussion.

The physics of train formation is not well understood. High-school physics teaches us that the kinetic energy of a body rises as the square of its velocity. In practice, the relation between the average velocity of meteoroids in a stream (stream velocity) and the percentage of trains will be much more complicated, and simulation models have to fix (a) how fast a meteoroid will lose its kinetic energy and (b) in which forms of energy the kinetic energy will be set in which proportions.

Baggaley (1975) states that the physical processes leading to meteor trains are not entirely understood. Ionisation would furnish too bluish a light, while the red wavelengths observed in train spectra could be due to molecule dissociation and recombination. Baggaley gives two conditions for such processes:

1. enough gaseous mass to furnish the molecules for the processes
2. low gas density (a high gas density will dissolve trains too fast to be seen).

Both of these factors are influenced by meteor speed. (1) Using experiments with artificial meteors, Friichtenicht & Becker (1973) found that slow meteors up to 25 km/s receive a significant drag and slow down measurably, while meteors faster than about 25 km/s lose their kinetic energy by ablation and keep their velocity while losing their mass (they worked with particles of a mass of about 10^{-16} up to 10^{-10} grams). So it seems logical that the faster the meteor, the faster it loses its mass by ablation, which should help train formation according to Baggaley (1975). (2) It is known from observations that faster meteors tend to begin glowing higher above the earth's surface (see for example Koschack et al., 1995, p.87). It seems reasonable to assume that the ablation process will also start at a higher altitude, so trains will last longer and are thus more likely to be detected.

The mass of a meteoroid should not be as crucial for train formation as its speed: in bigger particles, heating grows only with surface, while the mass to be heated grows with volume, so ablation will not rise very fast with particle diameter (depending on heat transport processes within the particle). Bigger particles will reach lower altitudes before being totally vaporised (if they don't split up, which is more likely for big meteoroids than for small ones).

Bellot Rubio (1992) listed train percentages of different streams, using data of the Spanish Meteor Society (SMS). He established a relationship between stream velocity and train percentage, that was probably flawed for two reasons:

1. he assumed a linear relation
2. he didn't take into account different r values in different streams.

With reference to point (1), a glance at observations (see Figure 4) shows that the percentage of trains rises much faster than linearly with stream velocity. There is reason to assume a higher order power function for theoretical reasons also (see above; theory can not give us a more precise hint which type of function we should assume; it could be that it is reasonable to take two functions to approximate the slow and fast branch; see Figure 2 and Friichtenicht & Becker, 1973). With reference to point (2), streams with a higher r values contain more weak meteors. This will reduce the number of train observations, since a train is always weaker than the meteor and is therefore less likely to be detected in a weak meteor than in a bright meteor. (Note that for this reason it is also crucial to control limiting magnitudes!)

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In the present study, I tried to overcome these problems by establishing empirically a power function relating meteor velocity and train percentage for particular meteor magnitudes.

2 Methods

Data used stem from observations (predominantly plottings) made by one single observer (BUCAN) in the last 4 years, according to IMO standard observing methods (Rendtel et al., 1995). Shower association of the plottings was made by the VISDAT-program (see IMO-homepage `www.imo.net` or Richter, 1999).

To establish a power function based on the available data, data were collapsed over streams of similar velocity. The result was six samples of meteors of similar size. For practical reasons, I compared only the meteors of the brightnesses $m = 2$ and $m = 3$: (a) they are seen often and leave trains reasonably often (evading ceiling- and floor-effects) (b) brighter meteors are seen often in the periphery of the field of view, which causes problems in shower association and train detection (turning the head and often losing short-lasting trains because of bad picture resolution at the periphery). Velocities for the cells were calculated as a weighted mean of the velocities of the streams collapsed over. Then a linear fit was calculated over the logarithms of percentages of trains and velocities in each data set.

In the course of the calculations, I noticed that observations with the moon present biased the data. It probably influences the limiting magnitudes for stars differently than the visibility of trains: stars are dot-shaped and long-lasting while trains are extended and short-lasting. This is likely to lead to far fewer observed trains (the problem is even more pronounced than with limiting magnitudes and meteors; there it is known that most observers see lower rates in moon-polluted observations, especially if they last long, e.g. one hour or more without break). For example, in my observations even the full moon did not lower the limiting magnitude for stars more than about 0.5 magnitude, but all the same I would see only about half of the meteors, and probably less than half of the trains than in an observation without the moon. An additional problem about moon-polluted observations in my data was that I observed with moonlight only at the maxima of the big showers, and they are not representative over velocities (LEO: 71 km/s; PER: 59 km/s).

3 Results

The meteors used were part of the total of 2682 stream meteors observed by BUCAN in the period from 1999 to mid November 2003. Figure 1 shows the obvious dependency of percentage of trains on stream velocity and meteor magnitude. Data points are plotted if 10 or more meteors were observed per data point. For comparison, there are also the train percentages of sporadic meteors in September (of course, they depend strongly on the source; evening observers would receive less trains, because of smaller velocity of the toroidal source compared to the apex source).

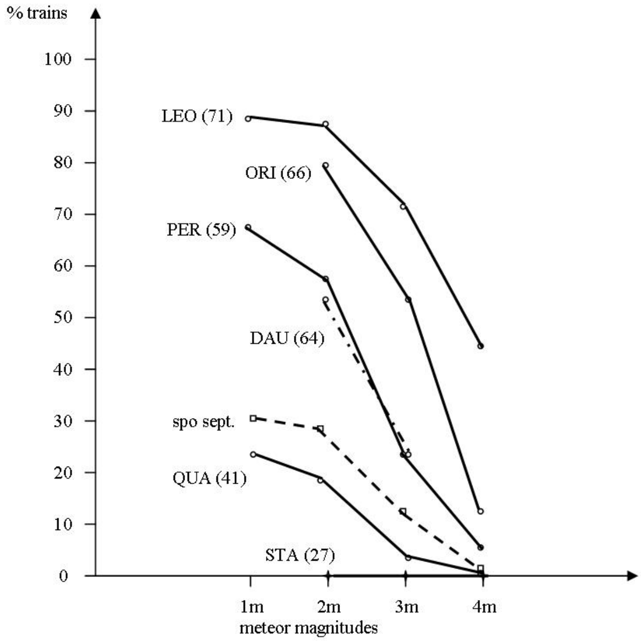

Figure 1 – Percentage of trains with respect to meteor magnitude and stream. Numbers in brackets are stream velocities in km/s. Only data points for more than 10 meteors are given.

Figure 2 shows the relation between stream velocity and percentage of trains at a particular meteor magnitude ($m = 3$). Points were plotted if there were 20 or more observed meteors. Observations were chosen only if there had been no moon. The graph shows zero trains up to about 40 km/s and then a fast rise. Unfortunately, there was not enough data for streams with median velocity (QUA and LYR, for example), so it is not clear if we should assume one function for all velocities or divide it in two branches, assuming qualitatively different physical processes (drag and slowing down for slow streams, ablation without slowing down for fast streams).

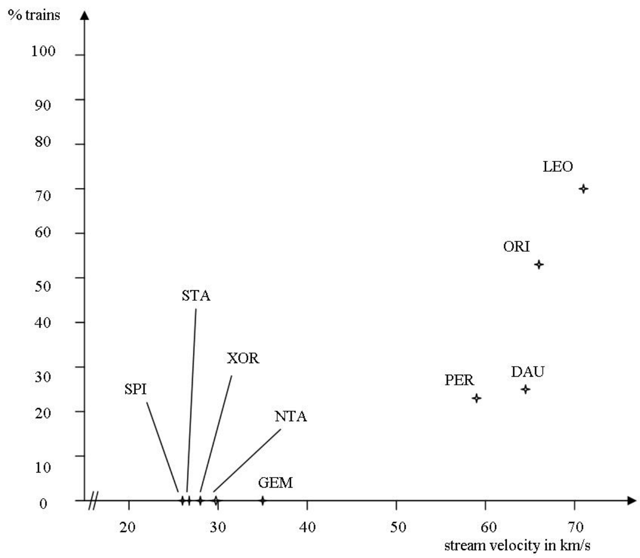

Figure 2 – Percentage of meteors with trains, according to stream velocities, for meteors of magnitude $m = 3$. Data points were given for streams with 20 or more observations only.

Table 1 – Calculated parameters for the whole dataset (including observations with moon contamination; limiting magnitudes range $m = 4.89$–6.90), separated for $m = 2$ and $m = 3$ meteors.

Table 1a: Parameters for meteors of $m = 2$.

Streams	n_{met}	n_{tra}	$\%_{\text{tra}}$	v	$\ln\%_{\text{tra}}$	$\ln v$
JBO-NIA	89.5	5.5	6.15	27.51	1.816	3.315
URS-PAU	65.5	2.5	3.82	34.85	1.340	3.551
SDA-LYR	59	8.5	14.41	41.32	2.668	3.721
HYD-PER	121	63.5	52.48	59.00	3.960	4.078
DAU-ORI	35.5	22	61.97	65.34	4.127	4.180
EGE-LEO	178	116.5	65.45	71.00	4.181	4.263
Mean					3.015	3.851
Standard deviation					1.144	0.347

$$\Rightarrow \quad r = 0.944^{**}$$
$$b = 3.110$$
$$a = -8.963$$

Table 1b: Parameters for meteors of $m = 3$.

Streams	n_{met}	n_{tra}	$\%_{\text{tra}}$	v	$\ln\%_{\text{tra}}$	$\ln v$
JBO-NIA	163.5	2	1.22	26.16	0.201	3.264
URS-PAU	84	2.5	2.98	34.83	1.092	3.550
SDA-LYR	55.5	4	7.21	41.98	1.975	3.737
HYD-PER	125.5	24.5	19.52	58.98	2.971	4.077
DAU-ORI	68.5	20.5	29.93	65.01	3.399	4.175
EGE-LEO	235.5	101	42.89	71.00	3.759	4.263
Mean					2.223	3.844
Standard deviation					1.273	0.359

$$\Rightarrow \quad r = 0.998^{**}$$
$$b = 3.540$$
$$a = -11.385$$

Abbreviations:
n_{met}: number of meteors in a cell
n_{tra}: number of meteors in a cell having a train
$\%_{\text{tra}}$: percent meteors with train (n_{tra} / n_{met} * 100%)
v: weighted mean of stream velocities according to number of meteors in a cell
ln: natural logarithm (base e)
r: Pearson correlation (** means significantly different from 0 with 99% probability)
b: slope of straight line fitting the logarithmic data
a: intercept of straight line fitting the logarithmic data

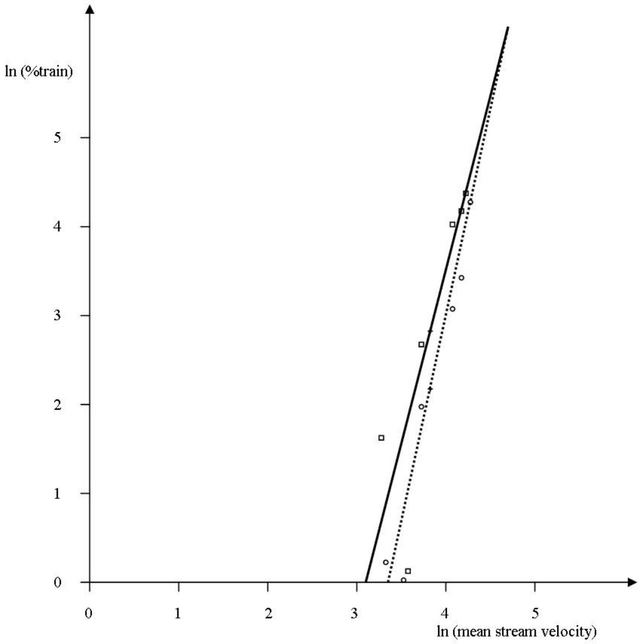

Figure 3 – The relation between stream velocity and percentage of trains in a log-log scattergram. squares are the $m = 2$ data (solid line for linear fit), circles the $m = 3$ data (dotted line for linear fit).

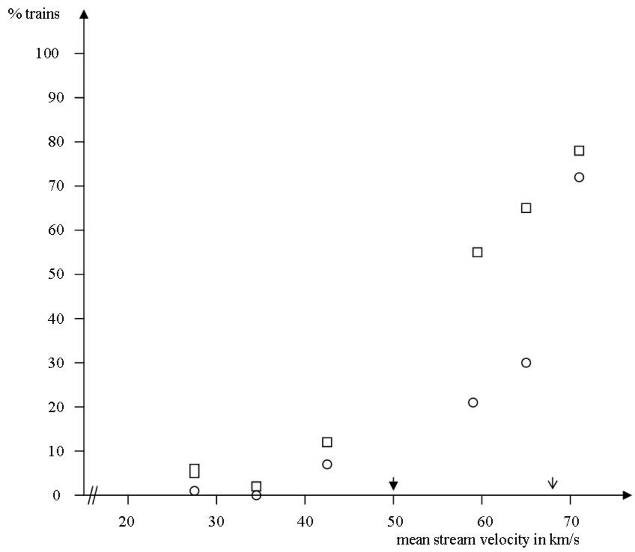

Figure 4 – Relation between stream velocity and percentage of trains on a linear scale. Squares are data for magnitude 2, circles for 3. The arrowheads mark the point of biggest slope (filled for $m = 2$, open for $m = 3$).

For the further analysis, data were collapsed over streams with similar velocity v, to reach reasonable sample sizes. A weighted mean for stream velocities was calculated according to the number of meteors from a stream (separately for $m = 2$ and $m = 3$). Net data for the six samples was converted to logarithms and correlated, and the slope of the linear fit was calculated, which is the exponent of the power function (Table 1 and Table 2). Table 1 shows all the data including observations contaminated by the moon, Table 2 only the data without observations contaminated by the moon (note the bigger exponent, showing more trains in weak meteors). Note that the sensitivity loss of the eyes in moon-polluted observations is not sufficiently reflected by the limiting magnitudes, because of much faster tiring of an observer in the bright sky.

With this model, the percentage of trains at $m = 2$ or 3 can be predicted with the formula: %trains=$e^a \cdot v^b$ [v in km/s] (e.g. for $m = 3$: %trains $= e^{-11.385} \cdot v^{3.54}$ $= 1.137 \times 10^{-5} \cdot v^{3.54}$).

Figure 3 shows the fit for both the $m = 2$ and $m = 3$ data, only for the observations without moon, in a log-log scattergram (slopes correspond to the exponent in the power function). Data for $m = 2$ and $m = 3$ differ more and more in the lower velocity range (probably because the brightness of the trains falls below the limiting magnitude for $m = 3$ meteors faster than for $m = 2$ meteors; one could test this thesis with $m = 1$ data, because the line should be similar to the $m = 2$ line). Note the dip of the 3.54 $\ln v$ data point: the cell contains mainly Geminid data. Eventually this could be a hint on the old supposition, that Geminids make few trains even if their low velocity is taken into account. One should test this supposition with an independent data set.

4 Some further ideas

During the calculations for this study, I was struck by the form of the curves connecting stream velocity and percentage of trains at a certain magnitude (Figure 4). If they are really S-shaped as it seems to me, then their form could tell us something about the ability of observers to detect trains. More specifically, differentiation of such an S-shaped curve would lead to a normal distribution, of which the mean would correspond to the limiting magnitude for meteor trains.

Taken the other way around, assuming a particular limiting magnitude would yield a relation between meteor velocity and relative brightness of a meteor train compared with the meteor. For example, Figure 4 shows the steepest slope for $m = 2$ meteors around 50 km/s (arrow in Figure 4). If we assume a limiting magnitude of $m = 6$ for trains, this means that trains at 50 km/s are 4 magnitudes weaker than their ‘parent’ meteors. For $m = 3$ meteors, the steepest part of the curve is at 68 km/s, which means that at 68 km/s, meteor trains are 3 magnitudes weaker than their ‘parent’ meteors. If we additionally compare different limiting magnitudes, it could be determined whether this relation varies or is constant: in other words, if the relations between magnitude and train formation on the one hand and between velocity and train formation on the other hand are statistically dependent or not. In any case it would be possible to determine if a stream meteor of a particular brightness should have a train or not at a particular limiting magnitude.

Taking this relation, trains could be used as an additional criterion for shower association (for example, a $m = 2$ meteor without visible train would be very unlikely to be a Leonid, given a limiting magnitude of $m = 6$). Note that this does not depend on the distance of the meteor, because both parts, meteor and train, occur in the same place.

The relation between velocities and percentage of

Table 2 – Calculated parameters for the whole dataset (excluding observations with moon contamination; limiting magnitudes range $m = 5.41$–6.90), separated for $m = 2$ and $m = 3$ meteors and combined for both.

Table 2a: Parameters for meteors of $m = 2$.

Streams	n_{met}	n_{tra}	$\%_{\text{tra}}$	v	$\ln\%_{\text{tra}}$	$\ln v$
JBO-NIA	88.5	4.5	5.09	27.49	1.626	3.314
URS-PAU	44.5	0.5	1.124	34.79	0.117	3.549
SDA-LYR	59	8.5	14.41	41.25	2.668	3.720
HYD-PER	100	57.5	57.5	59.00	4.052	4.078
DAU-ORI	34	22	64.71	65.35	4.170	4.180
EGE-LEO	49.5	39.5	79.8	70.88	4.380	4.261
Mean					2.836	3.850
Standard deviation					1.556	0.348

$$\Rightarrow \quad \begin{aligned} r &= 0.876^{**} \\ b &= 3.921 \\ a &= -12.260 \end{aligned}$$

Table 2b: Parameters for meteors of $m = 3$.

Streams	n_{met}	n_{tra}	$\%_{\text{tra}}$	v	$\ln\%_{\text{tra}}$	$\ln v$
JBO-NIA	159	2	1.258	27.36	0.230	3.309
URS-PAU	51	0.5	0.98	34.72	−0.0202	3.547
SDA-LYR	55.5	4	7.21	41.98	1.975	3.737
HYD-PER	111.5	24.5	21.97	58.98	3.090	4.077
DAU-ORI	65.5	20.5	31.3	65	3.444	4.174
EGE-LEO	45	32.5	72.22	70.88	4.28	4.261
Mean					2.166	3.851
Standard deviation					1.608	0.347

$$\Rightarrow \quad \begin{aligned} r &= 0.963^{**} \\ b &= 4.460 \\ a &= -15.011 \end{aligned}$$

Table 2c: Parameters for combined meteors of $m = 2$ and $m = 3$.

Streams	n_{met}	n_{tra}	$\%_{\text{tra}}$	v	$\ln\%_{\text{tra}}$	$\ln v$
JBO-NIA	247.5	6.5	2.63	27.41	0.966	3.311
URS-PAU	95.5	1	1.05	34.75	0.046	3.548
SDA-LYR	114.5	12.5	10.92	41.62	2.390	3.729
HYD-PER	211.5	82	38.77	58.99	3.658	4.077
DAU-ORI	99.5	42.5	42.71	65.12	3.755	4.176
EGE-LEO	94.5	72	76.19	70.88	4.333	4.261
Mean					2.525	3.851
Standard deviation					1.563	0.347

$$\Rightarrow \quad \begin{aligned} r &= 0.924^{**} \\ b &= 4.157 \\ a &= -13.482 \end{aligned}$$

Abbreviations: see Table 1.

trains could also be used the other way around, to determine (absolute) meteor velocities in large enough samples. An example of this can be seen in Figure 1: the train percentage of sporadics of September is situated between QUA and PER, which means that they have train numbers like a stream with a velocity between 40 and 60 km/s. Of course this could be pinpointed more narrowly with more stream data. In this manner, train data could for example be used as a rate-independent test for the apex theory (Znojil, 1995). Of course observing locations, times and centers of fields of view should be controlled for this (optimally using observers watching symmetrically to the equator and on the same longitude from both hemispheres). If the apex theory is correct, rising north of the apex should lead to more sporadic meteors with trains for a northern observer and less sporadic meteors with trains for a southern observer, so sporadic rates should be correlated with their percentage of trains.

So a lot can be done with meteor trains, as soon as observers (especially the ones observing around the year and not only at the maxima of big showers) send a lot of train data to Jan Verbert. Plotting data are more valuable, because shower association is more precise than with counting data.

5 Conclusion

The present study attempts to outline methods easy enough for non-professionals to pinpoint the relation of meteor magnitudes and stream velocities to their tendency to make trains (in fact, the most sophisticated technical device used for the calculations was a pocket calculator). Pending more work, these relations can be represented by the following formula:

$$\text{percentage of trains at about } m = 2.5 \\ = 1.396 \times 10^{-6} \cdot v^{4.157}$$

which is my best estimate. Better control of the limiting magnitudes and more equal weighting of streams (for example, using 100 meteors per shower, from observations with a limiting-magnitude range of $m = 6$ to 6.2) pinpoint the exponent behind v a lot, all we need to do this is M O R E D A T A! Moreover, my data (see Figure 2) does not allow us to say if a power function is really reasonable to approximate this relation. This could also be changed with more data.

At the very least it can be said that velocity is one (if not THE) major factor influencing the percentage of trains. It will control the main part of the variance, so an extraction of other factors needs a control of this factor (either by comparing two streams of the same velocity, or by removing the effect of velocity with a more stable formula). Removing the effect of velocity would make it possible to go into the chemical factor: can anything be said about the composition of the particles from the percentage of trains? A promising candidate to test this would be the Geminids, which made the drop in Figure 3. Eventually my exponent b of about 4.16 has to be lowered because of this dip.

Acknowledgements

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A fireball analysis from Spanish meteor observations

Orlando Benítez Sánchez [1] *and Francisco Ocaña González* [2]

Naked eye meteor records from Spain are used for an analysis of 3240 fireballs reported by members of the Sociedad de Observadores de Meteoros Y Cometas de España (SOMYCE) and by casual eye-witnesses from 1982 to 2000.
This analysis concerns various areas, such as statistical studies of the colours and the frequency of fireballs in annual meteor showers. Annual and diurnal variations are also discussed.
We describe the population index r for magnitudes brighter than $m = -2$ for ORI, VIR, AQU, TAU, CAP, QUA, GEM, LYR, LEO, KCG, PER and sporadic fireballs. The typical population index is always in the range $\simeq 1.2$ to 1.9, except for Perseids and Geminids.
An investigation of visual fireballs radiants was attempted with the Radiant software. The sample of fireballs (282 fireballs with the path reported) only shows evidence for the Perseids and Leonids.

1 The Spanish data set: observers and report form

Meteor observations have been carried out by SOMYCE members in Spain from 1982 to 2000. All the observations were reported on the FIDAC report form, and input into dbf FIDAC files. We took all meteors brighter than an apparent magnitude of -2 to be fireballs. The observers who contributed to this study are as follows:

> Acosta, José; Albacete Verdí, Salvador; Alonso Rivero, Gustavo; Alonso, Javier; Álvarez, J.; Álvarez, Raquel; Arranz, Pedro; Asociación Astronómica Complutense; Asociación Astronómica Tamiz; Asociación Valenciana de Astronomía; Barreda, Pepe; Bautista Rivas, Antonio; Bellot Rubio, Luis; Benavides, Rafael; Benítez Castellanos, Eusebio; Benítez Sánchez, Jesús; Benítez Sánchez, Orlando; Bennasar, Miguel Ángel; Bosch, Josep María; Brunet, Juana; Caballero Morillas, Javier Cáceres, José Antonio; Camarasa, Miguel; Campos, Javier; Carrillo, Alberto; Cervera, Oscar; Chambo, José; Company, Antonio; Contreras, José; Cordeo Cortegano, Miguel Ángel; Dalloz, Danielle; De San Ramón, María Elena; Del Valle Morell, Enrique; Díaz García, Ricardo; Díaz, José; Díaz, Valentín; Diego Rodríguez, Juan; Diez Smith, Silvia; Doreste, Domingo; Dueñas Mínguez, Marta; Even-Smith, Bev; FEMA, Federation of European Meteor Astronomers; Fernández Barba, David; Fernández Reyes, Sergio; Fernández Vigo, Adrián; Fernández, Francisco; Fernández, José María; Fernández, Raúl; Fernández, Ricardo; Figueres, Carles; Gámez Moreno, Cristóbal; García Díaz, Francisco Javier; García Martín, Fernando; García, Faustino; García, Francisco; Gil, Francisco; Gisbert, José; Gómez Domínguez, Daniel; Gómez Domínguez, Jose Antonio; Gómez Fernández, Inmaculada; Gómez, Juan; González, Domingo; González, Javier; González, Olga; González, Pedro Luis; González, Vicente; González, Víctor; Guixeras Romero, José Luis; Gutiérrez Corrales, Antonio; Hernández Cabrera, Miguel; Hernández de Andrés, Santiago; Hernández, Carlos; Jiménez Alvarado, Francisco; Jiménez del Barco, Manuel; Jiménez Medaño, Mar; Jiménez, Iván; Jiménez, María del Mar; Kidger, Mark; Leal, Jesús; Llodra, Jaime; Llopis, Edgar; Llorente, José; López Sánchez, Ángel; López, Antonio Esteban; Lozano, Charo; Maestre García, Hnos; Marián, Fernando; Marín Ancores, Daniel; Marín, Antonio Francisco; Marín, Manuel; Martínez Torres, Antonio; Martínez-Delgado, David; Masa, Edgardo Rubén; Mendiolagoitia Pauly, Alejandro; Molina, Vicente José; Muñecas Vidal, Miguel Ángel; Murías, Alfonso; Nicolás, Carlos; Ocaña González, Francisco; Olivera, Rosa; Ortega, Israel; Pérez Díaz, José María; Pérez, Vicente; Picazo, J.C.; Pineda, Carles; Pliego Carmona, Antonio; Portillo Hidalgo, José E.; Quetglas, Francisco; Ramón Rodríguez, Juan; Rancel, Alejandro R.; Redondo, Eva; Reyes Andrés, Francisco; Ripero, José; Rodríguez Bergall, Francisco; Rodríguez, Francisco Alberto; Rodríguez, Juan D.; Rodríguez, Juan Ramón; Rodríguez, Orlando; Román Reche, Antonio; Ruiz, Julián; Ruiz, Víctor Raúl; Rute, Ángeles; Sáez, Francisco; Salas, Henry; Santana Gil, Cayetano; Santos, J. L. ; Santos, Pablo; Saurina, Joan Miguel; Segovia Muñoz, Ginés; Selpa, Isabel; Serés, Jordi; Serra, Miguel Ángel; Sevilla Lobato, Francisco José; Solano Vinuesa, Manuel Ángel; Suárez Tejera, Máximo; Suárez, Juan L.; Suárez, Néstavo; Tejera Rodríguez, Miguel; Toral Jiménez, Gregorio; Torrell, Sebastiá; Trigo, Josep María; Tuero, Luis; Uroz, Miguel; Vanrell, Bruno; Vaquero, José Manuel; Vázquez Darías, Carlos Luis; Verde, Daniel; Vigil, Ester; Villalonga, Miguel Antonio.

In total, the observers registered 3240 fireballs. In Table 1 we show the number of fireballs by year and their relative percentages.

2 Sporadic background and presence of fireballs in meteor showers

The numbers of fireballs by solar longitude are represented in Figure 1 (January corresponding to solar longitude $\lambda_\odot = 300°$ and July to $120°$).

Fireballs require a different approach for sporadics and meteor fireballs. Out of 3240 fireballs, 3048 came from a known radiant (many of them being reported from the 1998 Leonid fireball storm activity on November 18th). The rest, 192 fireballs, were sporadics.

Figure 2 shows the sporadic fireball background during the whole year. The maximum in July and August is probably due to the greater number of observers then,

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Table 1 – Number of fireballs by year and relative percentages.

Year	*fireballs(N)*	*percent*
1982	11	0.34
1985	1	0.03
1986	16	0.49
1987	4	0.12
1988	8	0.25
1989	6	0.19
1990	36	1.11
1991	214	6.60
1992	48	1.48
1993	117	3.61
1994	38	1.17
1995	88	2.72
1996	158	4.88
1997	35	1.08
1998	987	30.46
1999	1024	31.60
2000	449	13.86
TOTAL	3240	100.00

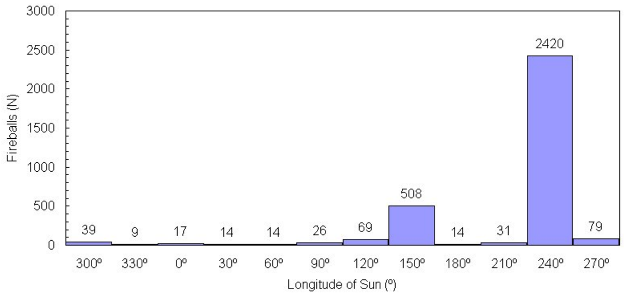

Figure 1 – Total number of fireballs (shower + sporadic) by solar longitude.

rather than a peak in the actual number of fireballs. Very low activity is observed from January to June, similar to the annual variation in faint sporadics meteors; this occurs again in September (with a minimum) to December. These variations before September could be produced by the largest number of observers over the summer period. The Orionids, Leonids and Geminids are evident in the Figure.

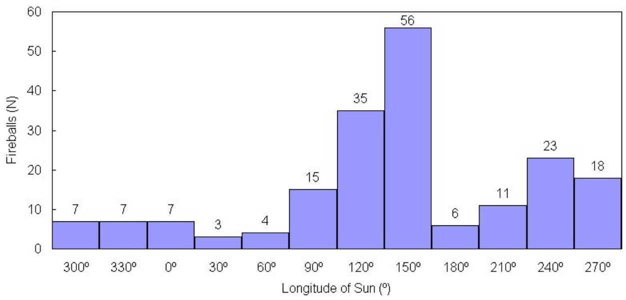

Figure 2 – Sporadic fireball background during the whole year.

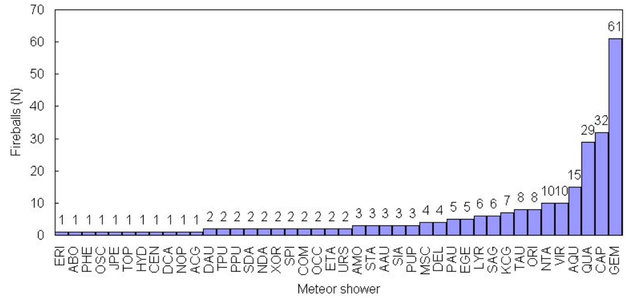

Figure 3 – Fireball classification by meteor shower. Perseids (N=424), Leonids (N=2366) and sporadics fireballs (N=192) are not shown on the bar graph.

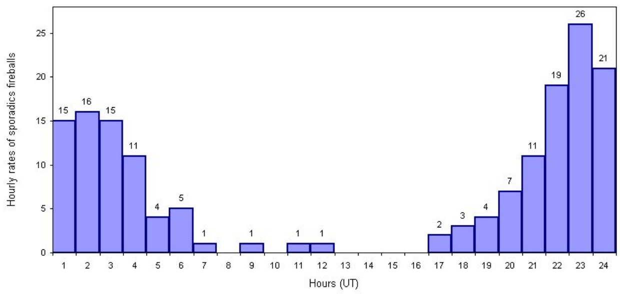

Figure 4 – Hourly numbers of sporadic fireballs. Only 163 of the 192 fireballs are shown as no time was reported for the others.

Figure 3 shows the number of fireballs for each shower, labelled according to the IMO list from 1995. Fireballs classified as Aquarids may not have come from any defined radiant but may have been sporadics. Since the Taurids were not classified as South Taurids or North Taurids, the same problem may occur. Perseids (424), Leonids (2366) and sporadics fireballs (192) are not shown on the bar graph.

As regards the diurnal variation in sporadic fireballs, the plot (Figure 4) accords with theory: the number of fireballs observed per unit time increases during the evening, with a maximum at $23^{\rm h}$. No fireballs were observed in the daytime, except some exceptionally bright fireballs. It is important note a possible ‘social effect’ when people get up to work at $06^{\rm h}$ (Rendtel & Knöfel, 1989).

3 Colours of fireballs

Fireball colours for different annual showers and sporadics, in normalized values, are shown in Figure 5. This colour is not necessarily similar to the normal meteor colour. Orange, blue and yellow are the most common for sporadics, and white for meteor showers, with differences between years and between meteor showers affected by the number of observations and different visual perception. Usually different witnesses reported different colours for the same fireball.

Table 2 – Normalized frequency of colours for fireballs in different meteor showers.

	White	Yellow	Orange	Red	Blue	Green
SPO	27.72	35.14	42.86	22.22	36.51	27.03
LEO	4.95	0.00	0.00	3.70	4.76	2.70
GEM	2.48	5.41	0.00	0.00	1.59	0.00
PER 1983-1990	0.99	10.81	14.29	18.52	1.59	2.70
PER 91	0.99	8.11	0.00	0.00	0.00	0.00
PER 92	0.50	0.00	7.14	7.41	0.00	0.00
PER 93	3.96	2.70	0.00	0.00	9.52	16.22
PER 94	0.50	0.00	0.00	0.00	6.35	5.41
PER 95	6.44	5.41	0.00	0.00	1.59	2.70
PER 96	1.98	2.70	7.14	3.70	0.00	2.70
PER 97	4.46	0.00	0.00	3.70	0.00	2.70
PER 98	11.39	0.00	0.00	0.00	9.52	2.70
PER 00	0.50	0.00	0.00	3.70	0.00	0.00
PER 83-00	33.17	29.73	28.57	37.04	28.57	35.14
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00

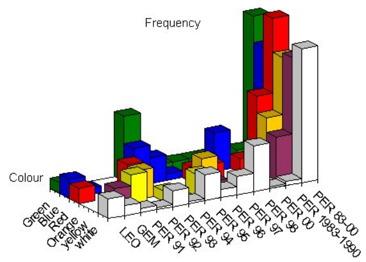

Figure 5 – Colours of fireballs. Data from Table 2.

4 Analysis of population index for fireballs of meteors streams and sporadics

The ratio between the meteor numbers in any magnitudes class $m+1$ and in class m is nearly constant over m. This ratio is called the population index r:

$$r = \frac{N(m+1)}{N(m)} \tag{1}$$

where $N(m)$ is the number of meteors within half a magnitude of m.

This population index may not be constant over the whole magnitude range. Equation (1) is also valid for the cumulative number $\Phi(m)$, the number of meteors of magnitude m and brighter. The relationship is:

$$r = \frac{N(m+1)}{N(m)} = \frac{\Phi(m+1)}{\Phi(m)} \tag{2}$$

so we can write (choosing $m = 0$ for our zero-point):

$$\Phi(m) = \Phi(0)r^m \tag{3}$$

(Koschack & Rendtel, 1990; Rendtel et al., 1995).

If we take logarithms of equation (3) we obtain:

$$\log(\Phi(m)) = m\log(r) + \log(\Phi(0)) = ma + b \tag{4}$$

where $\log(\Phi(0)) = b$ (the Y value at the intersection with the Y axis) and $\log(r) = a$ (the slope).

If these are plotted on a graph, the slope a can be measured and we obtain r as $r = 10^a$.

To determine the error in our estimation we use the formula $\sigma = 4.07N^{-0.764} + 0.2$, where N is the number of fireballs or meteors counted, σ is the standard deviation, and this expression is valid in the interval $10 < N < 400$ (Koschack & Rendtel, 1990, p.132).

The probabilities of perception for meteors brighter than magnitude -2 were assumed to be 1.0 for whole range. Further values of r derived from magnitude data are shown in Table 3.

The population index r is typically in the interval $\simeq 1.2$ to 1.9. Some of these values, e.g. those for KCG, must treated with caution because of the low number of fireballs reported. The Perseids (2.04 ± 0.55) have a somewhat different r from their normal (non-fireball) meteors. The Geminids are quite different, with $r = 3.14 \pm 0.38$, greater than their normal meteors.

If we examine Figure 6 (sporadics *vs.* showers), a discontinuity seems to occur around $m = -6$ to -7 with a different slope. However, the distribution of numbers of fireballs over the whole range of magnitudes is relatively smooth: obviously, the 'fainter' the fireballs, the greater the number.

Figures 7 and 9 show the cumulative number $\Phi(m)$ *vs.* magnitude m. In this case, we are interested in seeing any possible linear relation in the whole magnitude range. If one were found, a unique r value could be computed in the interval. With this in mind, we compare the slopes of all the showers.

The cumulative function of the minor showers shows that most of them have quite similar slopes. The similar slope (and thus r) for sporadics and Virginids is very interesting. Certainly the Virginids are affected by plotting errors, and many meteors recorded as Virginids may actually be sporadics. For α-Capricornids and Aquarids, both near the 'ecliptic concentration', this problem does not occur because the shower associ-

Table 3 – Population Index for some major and minor showers. SHO: all meteor showers. Note: the fourth column is the correlation coefficient r^2, not to be confused with the population index, also traditionally called r, described in the last two columns.

	Intercept b	Slope a	r^2 (see note)	No. of fireballs	$r\pm$error	r for normal meteors
ORI	1.476	0.235	0.999	10	1.72 ± 0.9	2.9
VIR	1.216	0.091	0.962	10	1.23 ± 0.90	3.0
AQU	1.485	0.241	0.978	11	1.74 ± 0.85	$\simeq$ 2.9 to 3.4
TAU	1.780	0.248	0.990	17	1.77 ± 0.67	2.3
CAP	1.879	0.186	0.984	29	1.53 ± 0.51	2.5
QUA	1.677	0.196	0.952	29	1.57 ± 0.51	2.1
GEM	2.807	0.497	0.998	61	3.14 ± 0.38	2.6
LYR	1.096	0.157	0.999	6	1.44 ± 1.24	2.9
LEO	1.791	0.162	0.913	34	1.43 ± 0.49	2.5
KCG	1.318	0.219	0.987	8	1.66 ± 1.03	3.0
PER	3.517	0.349	0.954	407	2.04 ± 0.55	2.6
SHO	3.287	0.264	0.989	622	1.83 ± 0.23	$\simeq$ 2.5
SPO	2.294	0.119	0.952	183	1.29 ± 0.31	$\simeq$ 3.0

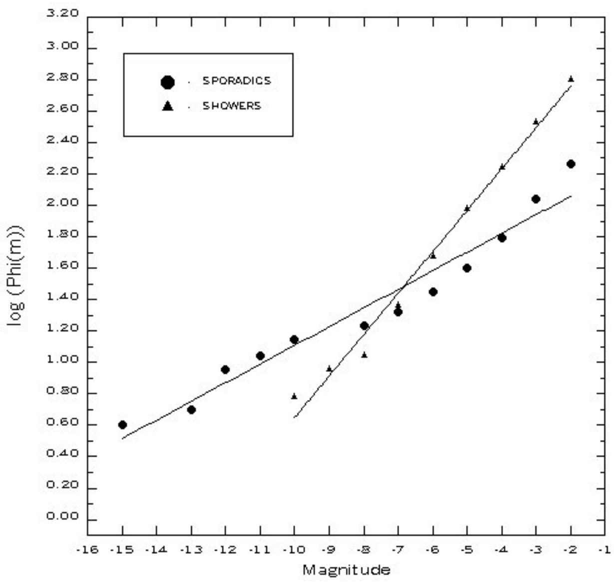

Figure 6 – Cumulative meteor number $\Phi(m)$ on a logarithmic scale *vs.* apparent magnitude for sporadics and all meteors from any know shower.

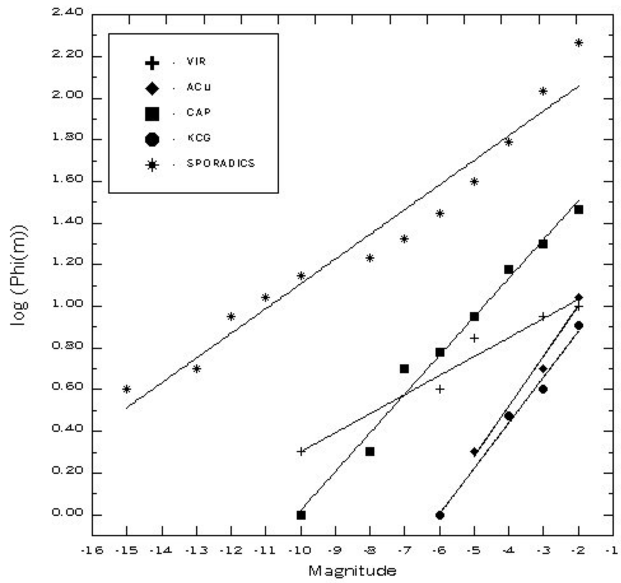

Figure 7 – Cumulative meteor number $\Phi(m)$ on a logarithmic scale *vs.* apparent magnitude for sporadics, Virginids, Aquarids, α-Capricornids and κ-Cygnids.

ation can be made unambiguously thanks to the plots on meteor charts.

In the major showers, there is a great difference between Taurids and Geminids. Geminids and Taurids come from old progenitors, like the asteroid 3200 Phaeton and the well know comet 2P/Encke, so one would expect their slopes to be similar. The difference could be explained by the different number of observations reported from both showers.

5 Fireball radiants

Using the available data in the SOMYCE fireball database, an investigation of the visual shower radiants and the fireball radiants was attempted with the Radiant software. Our results are tentative, because only 282 fireballs from the total of 3240 had a reported path.

We only found observational evidence for two radiants of the IMO list (Table 4). None from the Terentjeva radiant list have been reported in our visual data.

The results obtained can be summarized as follows:

- Perseid and Leonid fireball radiants have been detected. The agreement in RA and Dec with the IMO list is good for the Perseids, but our Leonid radiant is somewhat south of the IMO one.
- Large radiant areas occur because observers were counting meteors during their major shower observations and did not make plots. Moreover, especially with the Leonids, inexperienced observers make their first plotting observations, leading to unreliable data with highly dispersed paths.

The Leonid radiant is shown in Figure 8. For details see Table 4.

Table 4 – Radiant computations for Perseids and Leonids. The probabilities method was applied to the Perseids, while the Leonids were computed by the tracing method (which lacked geocentric velocities, marked with a T in the V_∞ column). The Perseids must be treated with caution because of the low number of fireballs reported (5). The IMO radiants are given for the Leonid maximum date and July 25 for the Perseids.

IMO code	Solar longitude $\lambda_\odot$ Range used	Solar longitude $\lambda_\odot$ Central value	Pixel size	Number of meteors displayed	V_∞	Observations RA α	Observations Dec δ	IMO data RA α	IMO data Dec δ
PER	$123\overset{\circ}{.}65$ to $128\overset{\circ}{.}12$	$126\overset{\circ}{.}91$	$0\overset{\circ}{.}5$	5	60	$24\overset{\circ}{.}96$	$+54\overset{\circ}{.}06$	23°	+54°
LEO	$232\overset{\circ}{.}91$ to $236\overset{\circ}{.}41$	$235\overset{\circ}{.}16$	$1\overset{\circ}{.}0$	29	T	$153\overset{\circ}{.}84$	$+14\overset{\circ}{.}74$	153°	+22°

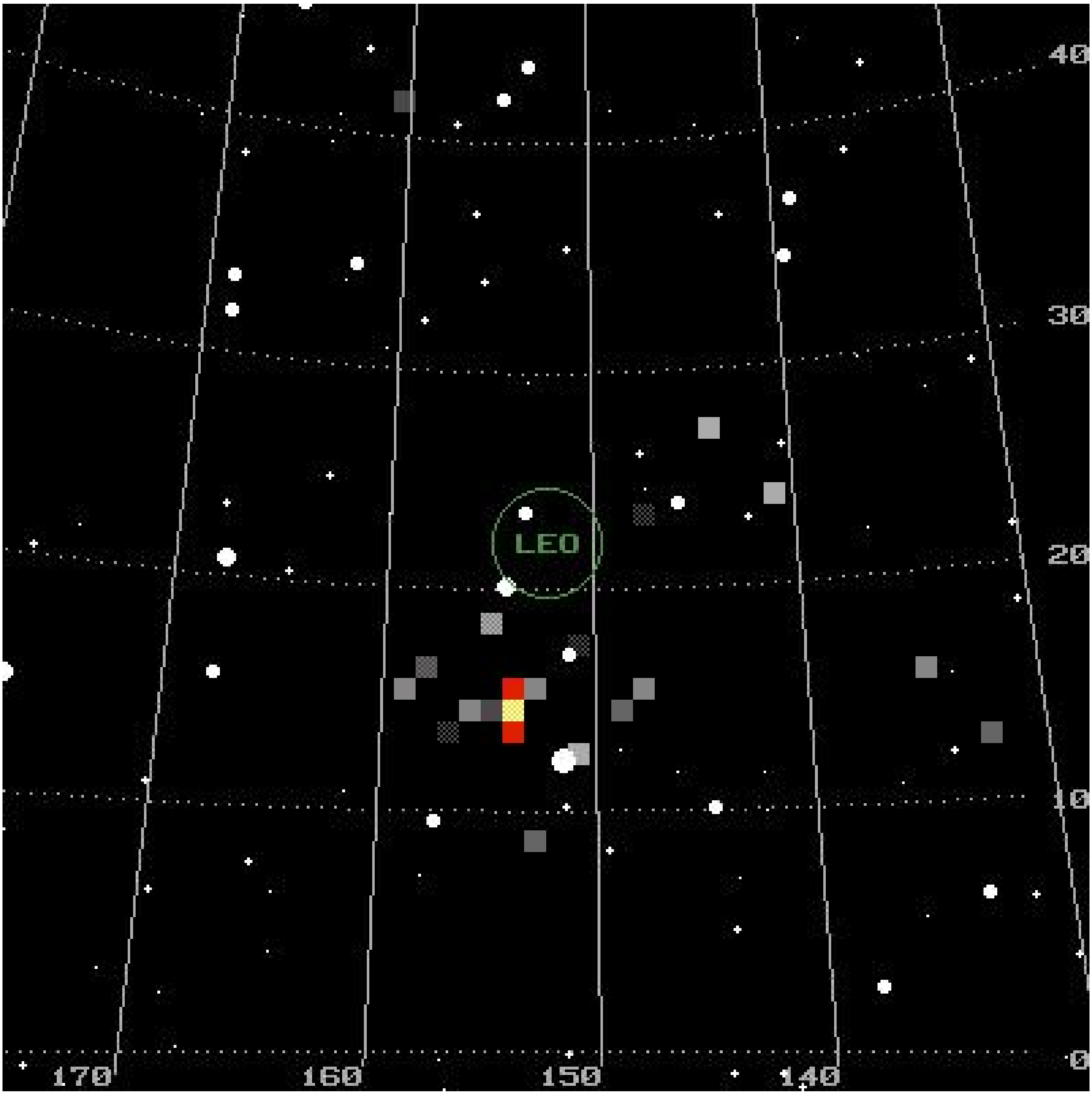

Figure 8 – Leonid fireball radiant, somewhat south of the typical position for faint meteors.

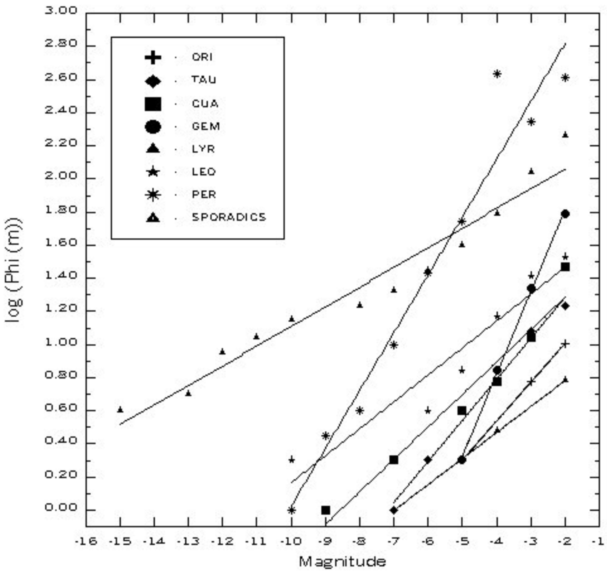

Figure 9 – Cumulative meteor number $\Phi(m)$ on a logarithmic scale *vs.* apparent magnitude for sporadics, Orionids, Taurids, Quadrantids, Geminids, Lyrids, Leonids and Perseids.

6 Conclusions

This paper show clearly that more accurate plots and reports of visual fireballs are necessary to obtain reliable radiant positions. Observations must be reported on the standard FIDAC form.

A complete treatment of fireball topics requires a large sample of visual records or, better, photographic and video reports. Chart plots are very important for correct meteor shower association and more precise r values.

Acknowledgments

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History

Meteor Beliefs Project: 'meteor' and related terms in English usage

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Various past and present meanings of the terms 'meteor', 'shooting star' and 'falling star' are examined, along with some similar, derived terms.

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1 Introduction

In previous Meteor Beliefs Project articles, we have examined chiefly beliefs about what we still modernly recognise as meteors, that is streaks of light in the night sky. This time, I want to look more closely at just what 'meteor' means, and has meant, in English, as well as some related terms. My main reference source for this has been the 20-volume Oxford English Dictionary (Simpson & Weiner, 1989), here cited as *OED*, with the volume and page numbers following in Roman and Arabic numerals respectively. I have secondarily drawn on Parrish & Crossland (undated) for a little added interest and colour. Although this latter work was not given a publication date, internal evidence and its likely purchase date suggest it was probably published in 1934 or 1935, a period when some now outdated meteoric terms were still in common and scientific use.

I must mention too that Martin Beech, in his excellent Makings of Meteor Astronomy series in WGN (Beech, 1993), touched briefly on the origins of the word 'meteor' in English. A couple of the dates he gave were slightly out, however, for the first appearance of 'meteor' in the language (too late), and for when 'meteors' became solely applied to 'shooting stars' (too early).

2 'Meteor'

The word 'meteor' is derived from the Latin *meteorum*, from the Greek *meteoron*, in its plural form meaning atmospheric phenomena or anything in the heavens. It is the substantive use of the Greek *meteoros*, which means 'raised', 'lofty', or in a more figurative sense, 'sublime'. Breaking down the Greek gives *meta*, 'beyond', and the verb *aeirein* 'to raise' or 'to lift up'. Interestingly, given that the first attested English written use of 'meteor' was in 1471 (*OED* IX, 684), the term was known in French literature by the 13th or 14th centuries, as 'météore', so the origins in English may be directly either from medieval Latin, or French, or both, and cannot be further recovered with our present knowledge. As normal with dictionary information, the earliest oral use will predate the written evidence by a variable timespan, potentially by several centuries for medieval and earlier sources.

In the order given by the *OED* (IX, 684–685), the meanings of 'meteor' are as follows. Firstly, the word can be applied to any atmospheric phenomenon, as its Greek roots indicate. There are four primary classes of such phenomena: aerial or airy meteors, which comprise the winds; aqueous or watery meteors, which include all forms of atmospheric precipitation, such as rain, snow and hail, but also things like mist, fog, frost, dew and even clouds; luminous meteors, which are not the 'shooting-star' type, but consist of other phenomena such as the aurora, the rainbow or any of the halo effects seen mainly with the Sun or Moon; and finally igneous or fiery meteors, which do include 'modern' meteors, and lightning, ball-lightning, will o'wisps (*ignis fatuus*, marsh lights or candles), or other similar effects, too. Most of these terms are now entirely obsolete in English usage, but not by very long, as the OED lists a series of references running between 1471 and 1905. Meteorology retains the term 'hydrometeor' for any liquid or solid water particle in the atmosphere (*OED* VII, 531–532, under 'hydro-').

Looking at mid-19th century information suggests the preferred term for shooting-stars then, in the scientific literature at least, was 'luminous meteors', not 'fiery' ones, however. Such a term appeared in a variety of reports of the time (e.g. Challis, 1867), and the British Association for the Advancement of Science (BAAS; founded 1831) was reported as having a 'Luminous Meteor Committee' from circa 1862. This 'Committee' may have been only an *ad hoc* grouping, despite the fact that notables such as Alexander Herschel, Robert Greg, James Glaisher and William Denning were all involved with it. Herschel provided details on observations of 'luminous meteors' to the BAAS annual reports from 1862–1881, which may indicate the effective life of the 'Committee'. Earlier, 'luminous meteor' reports were submitted to the BAAS by the Reverend Professor Baden Powell from 1848–1853. Details on Herschel's and Powell's activities in this regard were taken from the Dictionary of National Biography (Lee, 1912, 1896 respectively). 'Fiery meteors' was still in use then, as well as the more general 'meteor' for almost anything in the sky, as shown by Mitchell (1866–67), for instance. However, this seems to have been more among the poetic or philosophical communities. The Reverend Mitchell himself was Vice-President of the 'Victoria Institute or Philosophical Society of Great Britain' (formed 1865).

The second class of meanings in the OED centres on a more familiar meteor type, *A luminous body seen temporarily in the sky, and supposedly belonging to a lower region than the heavenly bodies*, (*OED* IX, 684), or more succinctly, *a fireball or shooting-star* (loc. cit.).

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The OED also notes that, during the 17th century, 'meteor' was used to mean a comet, something now considered entirely obsolete. The dated examples run between 1593 (from Shakespeare's 'Richard the Second' — see (McBeath & Gheorghe, 2003)) and 1878, although the term remains current of course.

Still under this second class is the term as applied, largely obsoletely, to other phenomena from the 'luminous' and 'fiery meteors' categories listed above, such as the aurora and the *ignis fatuus*, with dated texts illustrating this usage from 1592 to 1868. Two other forms include the obsolete poetic phrase *next the meteors*, meaning high above the ground (dated to 1638, before a clear understanding of just how high this meant was gained) and 'meteor' as applied loosely and incorrectly to a meteoroid, for which only two examples are cited, in 1884 and 1903, although this misunderstanding continues to be perpetuated in the popular media.

The OED's third class covers the figurative uses of the shooting-star form of 'meteor', giving examples from 1590 to 1769. Sense four is a plural usage of 'meteors' as an obsolete term for a treatise on, or published study of, meteors, in the late 16th to mid 17th centuries, such as William Fulke's *Meteors*. This was first published in 1563, and discussed fiery, airy, watery and, curiously, earthy, meteors. This followed the ancient Greek scheme of four elements — fire, air, water and earth — which made up the visible universe. Much of this remained in the 'elemental' concept of meteors, as covered above, but omitted earthy meteors. Fulke included earthquakes, minerals and metals found inside the Earth in his text, giving an idea of how all-pervasive he believed meteors to be.

Sense five has 'meteor' as the name for a piece of early 19th century confectionery, made from three egg whites, a pound of sugar made into syrup (about 450 g), *and any Essence you please*. The OED does not give the method of manufacture, though the ingredients sound like those for meringue, a very light, airy, typically white type of cake or sweet pie topping. Referring to the original cookbook (Jarrin, 1827, p. 195), under 'No. 441. — Meteors', confirms this view. The method to make meteors is given thus:

> Put on the fire a pound of syrup in a pan that has a lip to it, and boil it to a *blow*; in the mean time beat up the whites of the eggs, taking care to have them ready the moment the sugar is at the blow; pour the syrup in lightly to the eggs, and continue turning it till it is compact, smooth, and shining; lay it on a paper, in drops as large as a penny, and dry it in the stove; then take off the meteors, by wetting the papers at the back. To give them a proper shape, you must have frames in paper; they may be made of all colours, and may be candied. (See *Candy*). — You may also make them small like drops, but you must observe, that as you take them off, they must be neatly joined where they have been moistened, and they will then stick together.

'Blow' means boiling so the syrup is foaming, in this context, and a penny coin would have been about 3 cm in diameter. With greaseproof paper formers, it should be possible to make meteor-shaped 'meteors' like this. Maybe such 'meteors' could be introduced as a sweetmeat at IMCs, or at any other gathering of meteoricists?

Next come the various usages of meteor in combination with other words. Most of these hold no surprises, but three obsolete ones are of some note. 'Meteor-cloud' (cited from the Century Dictionary of 1890) was a meteor train; 'meteor-current' was a meteoroid stream (noted in Cassell's Encyclopaedic Dictionary of 1885); and 'meteor-steel', which was alloyed steel, though not necessarily meteoritic iron (which can be very similar to the alloy stainless steel).

The final meanings relate to the figurative uses of someone or something flashing or burning like a meteor (first referred to in 1711), and as something of short duration, or moving swiftly (where the earliest remarked use is dated 1803).

3 'Meteor'-related terms

Further on from 'meteor' (*OED*, IX, 685) are a number of other similar terms, including things like meteorology, which were earlier more closely related to modern meteors than is currently the case. Some are of more interest however. 'Meteorette' (1876) sounds like a small meteor, and so it was, but of a lower-atmosphere type.

'Meteoric' has greater promise, as pertaining to 'fiery' meteors, or consisting of them (first cited 1812). It was also an obsolete term referring to the mid-air region, or as meaning lofty or elevated (first usage is given as 1631), and it still remains in rare use as a general term for the atmosphere and its phenomena, although it was commoner so in the 19th century. Another meaning is found in botany from 1789 onwards, referring especially to flowers dependent on atmospheric conditions for their opening and closing, or sometimes to fungi needing specific atmospheric conditions to fruit, for instance. 'Meteoric-paper' was natural flannel; 'meteoric-steel' the meteor-steel mentioned above, while 'meteoric' still enjoys similar figurative connotations to 'meteor' — swift-moving, irregularly or briefly brilliant, and so forth.

'Meteorize' is noted as meaning 'to vaporize', although this is attributed to only a single source, John Evelyn's *History of Religion*, written in a set of volumes between 1657 and 1683. The term appears to have no especial relevance to 'our' sort of meteors in this respect. Its commoner, 19th century medical, use derives from the Greek *meteorizomenos*, first recorded in Hippocrates' 'Epidemics', IV.41 (Smith, 1994, pp. 134–135). This dates to circa 410 BC, though it was probably not written by Hippocrates himself. It remains in modern use as 'meteorism' (see Macpherson, 1999, p.351), and is a pathological gas-induced swelling of the bowels, better known as suffering from flatulence. . .

Moving meteorically-swiftly on, Parrish & Crossland (undated, p. 614) list terms under 'meteor' including 'meteorolite' for a meteorite, and 'meteoric shower' for meteor shower, now obsolete in these respects, though not when this dictionary was prepared. The '-lite' element derives from an alteration of the Greek '-lith', = stone; hence 'aerolite', from the Greek 'aer', 'aera', meaning air or atmosphere, and lith/stone, a 'stone-of-the-air' or one fallen to earth through the atmosphere, that is a meteorite. Unfortunately, the term does not enjoy an early origin, dating firstly only to 1815 in English (sometimes replaced by the more pedantically-accurate 'aerolith') and, until its modern obsolescence, in more recent times it was used generally for stony meteorites (*OED* I, 203).

Two last OED items, both from IX, 686. 'Meteoromancy' is foretelling the future by observing meteors, attested in English sources from 1797 in the OED, but known as a practice from ancient Mesopotamian texts back to the late second millennium BC (on which (Bjorkman, 1973) remains the essential main work). 'Meteoroscope' is listed as an instrument for measuring the apparent path of a meteor, cited to Funk's Standard Dictionary of 1895 by the OED's editors, and not yet considered obsolete by them. In fact, this meteoroscope was invented by James Challis of Cambridge University, as an aid to observing the 1866 Leonids. It was basically a sighting-bar on a tripod, used to mark some unstated point, presumably around the middle of the meteor's trail, in altitude and azimuth. The device and its observations were described in (Challis, 1867). The OED editors give an earlier meaning too, as an unspecified instrument for observing any objects in the heavens, not meteors particularly.

This earlier instrument is cited to Act 2, Scene 4 of Thomas Tomkis' anti-astrology satirical play from 1615, 'Albumazar: A Comedy'. The quote in the OED is actually from Act 2, Scene 5; lines 931–933 of which, spoken by the 'great astrologer' Albumazar, run: 'With Astralobe and Meteoroscope,/ Il'e finde the *Cuspe* and *Alfridaria*,/ And know what Planet is in *Cazimi*.' (Dick, 1944, p. 100, but here with the long-s's of the original amended to the short modern form).

Cuspe, *Alfridaria* and *Cazimi* are astrological terms of no relevance to meteors, and on which (op. cit., p. 186) gives further details. 'Astralobe' is a genuine mis-spelling of 'astrolabe', possibly an error originally, possibly for comic effect. 'Albumazar' is an improved adaptation of Giambattista della Porta's Italian play 'Lo Astrologo' (published in Venice in 1606; (Dick, 1944) provides a detailed discussion and commentary on this important aspect). Thus it is possible to see that both a correctly-spelt 'astrolabe' and 'meteoroscope' feature in the original Italian version. If 'meteoroscope' were only in Tomkis' text, it might be tempting to think it simply an early term for the telescope. In fact, Tomkis' 'Albumazar' has long been known as containing the earliest English description of the telescope, here called the 'perspicil', in Act 1, Scene 3, lines 236–276 (Dick, 1944, pp. 80–82, and notes on pp. 169–170). 'Perspiculum', or one of its similar-sounding variants, was the name used for the telescope by, for instance, Galilei and Kepler before 1611 (cf. *OED* XVII, 731 'telescope' and XI, 608, 'perspicil').

'Albumazar', Act 1, Scene 4, line 352 (Dick, 1944, p. 84), gives an additional mention of 'meteoroscope', where the 'great astrologer' himself is named as *Albumazar Meteoroscopico*, as also in the Italian original (op. cit., p. 172). 'Meteoroscopics' (*OED*, IX, 686) is an obsolete term for the science of observing the stars, and 'meteoroscopy' (ibid.) a rare word for the observation of stars, especially relating to astrology, hence 'meteoroscopist', an observer of stars or an astrologer, all words dating from the 17th to 19th centuries, according to the OED. From this, it follows that a 17th-century 'meteoroscope' might be a name applied to any instrument to aid an astrologer or astronomer in observing the heavens, not necessarily any particular one. 'Albumazar', as an entertaining text against astrological prognostications, is certainly well worth reading, and deserves to be more widely appreciated by the modern astronomical community.

4 'Shooting-' and 'falling-stars'

Naturally, the OED deals with these terms, as meaning meteors in both cases (XV, 315 and V, 696 respectively), first dating falling-stars to Fulke's *Meteors* of 1563, and shooting-stars to 1593 (again from the 'Richard the Second' Shakespearean quote noted before). However, the Westminster Dictionary describes a shooting-star in somewhat more poetic terms than the OED (Parrish & Crossland undated, p. 918): **shooting star,** *an incandescent meteor moving suddenly across the sky.* Parrish & Crossland (op. cit., p. 361, under 'fall') give 'falling-star' as being an aerolite, which from their own definition (op. cit., p. 27) signifies a meteorite. This seems to indicate an early 20th century distinction between a shooting-star as a meteor which passed swiftly across the sky only, and a falling-star which physically descended to the surface. There is no comment concerning this subtle difference in the later OED, where both terms are regarded as entirely synonymous. Indeed, the definition for 'falling-star' is given as *A meteor, a shooting star* (*OED*, V, 696).

One last definition for 'shooting-star' (*OED*, XV, 315) is from the USA, as a western common name for the American Cowslip, *Dodecatheon meadia*, first mentioned thus in 1856. Given the starlike appearance of many flowers, it would not be unexpected to find other comparable common or folk names.

5 Conclusion

'Meteor' as a term in the past has clearly enjoyed a much broader range of meanings than it has more currently. Given its rather vague Greek origins, concerning anything in the skies, this is not surprising. When using older texts, it must be remembered that a meteor need not be just what is now recognised as such, nor make assumptions based only on current perspectives. Even the subtle differentiation between a shooting- and a falling-star seems to have been lost within half a century, living memory for a few people who remain closely associated with meteor astronomy today, for instance. Now, bring on those meteor cakes!

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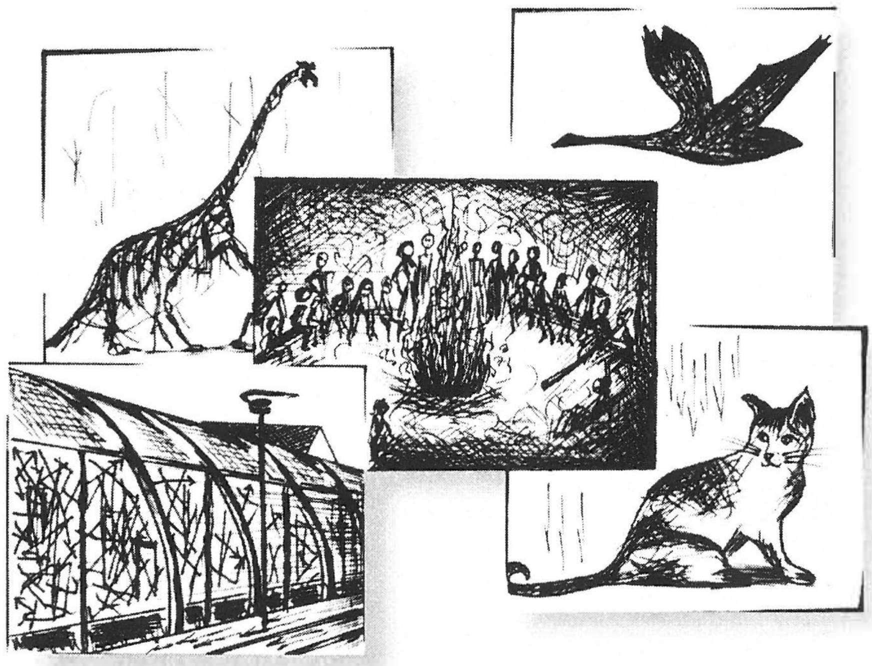

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