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Editors

Advances in Meteoroid and Meteor Science

Foreword by J.M. Trigo-Rodríguez, F.J.M. Rietmeijer, J. Llorca and D. Janches

Previously published in *Earth, Moon, and Planets*, Volume 102,
Issues 1–4, 2008

Springer

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Cover illustration: South Taurid fireball of magnitude -9 appeared on October 13th, 2007 at 23h48m50 ± 10s UTC. The fireball appears projected over the Pleiades (M45) cluster in this casual picture taken by Mario Ximénez de Embún from Marugán, Segovia, Spain. A Canon 350D camera was used with a 200mm f:2.8 lens plus a Sigma 2X duplicator. The camera was mounted in piggy-back of a telescope.

Backcover illustration: Daylight bolide photographed by Maria M. Robles from Santa Columba de Curueño (León). This magnitude -18 bolide appeared on January 4, 2004, and announced the fall of the Villalbeto de la Peña meteorite studied by the Spanish Meteor and Fireball Network (SPMN). A total mass of more than 3 kg of L6 ordinary chondrites were recovered by researchers of the Spanish Meteor and Fireball Network (SPMN). For comparison, the Moon is clearly visible on the left.

Library of Congress Control Number: 2008923259

ISBN-978-0-387-78418-2 e-ISBN-978-0-387-78419-9

Printed on acid-free paper.

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springer.com

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Preface

Josep M. Trigo-Rodriguez · Frans J. M. Rietmeijer · Jordi Llorca · Diego Janches

Originally published in the journal Earth, Moon, and Planets, Volume 102, Nos 1–4.
DOI: 10.1007/s11038-008-9228-0 © Springer Science+Business Media B.V. 2008

This volume is a compilation of articles that summarize the most recent results in meteor, meteoroid and related fields presented at the Meteoroids 2007 conference held in the impressive CosmoCaixa Science Museum in Barcelona, Spain. The conference took place between 11 and 15 of June and was organized by the Institute of Space Sciences (*Consejo Superior de Investigaciones Científicas*, CSIC) and the *Institut d'Estudis Espacials de Catalunya* (IEEC). Researchers in meteor science and supporting fields representing more than 20 countries participated at this international conference where 126 presentations were delivered in oral and poster forms. The 69 papers included in this volume represent the work of 154 authors from about 70 different institutions across the globe. The Meteoroids conference is an international meeting that takes place every 3 years since the first one held in Bratislava, Slovakia in 1994. The 2007 meeting was the first one where samples of a comet, 81P/Wild 2, were available from the NASA Stardust mission, and results from laboratory characterizations were presented and discussed. Seemingly aware of the upcoming meeting a bolide was observed over La Mancha, Spain, on May 10. The first five recovered fragments of this event that is known as the "Puerto Lápice" eucrite meteorite fall were shown at the meeting. Eucrites are linked to asteroid 4 Vesta, which is the source of differentiated achondrite meteorites that are igneous rocks formed from basaltic magmas. Puerto Lápice and Wild 2 are at the opposites of the spectrum of

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J.M. Trigo-Rodriguez et al. (eds.), *Advances in Meteoroid and Meteor Science.*
DOI: 10.1007/978-0-387-78419-9_1

meteoroid compositions that can interact with the Earth's atmosphere. Laboratory analyses of this meteorite and the comet dust will be critical to elucidating the properties of these known meteoroid-producing sources.

Technological advances in meteor and meteoroid detection, the ever-increasing sophistication of computer modeling, and the proliferation of autonomous monitoring stations continue to create new niches for exiting research in this field. They also allow the built-up of long-term databases providing crucial statistics needed to understand origins and distributions. It was especially gratifying to witness at this meeting the emergence of laboratory-based meteor science.

The conference gave a comprehensive overview on meteoroid and meteor science in two broad-based thematic categories. The first category covered detections, observations and measurements techniques many of which were described in great detail by invited speakers. The contributed presentations in this category focused on the formation of meteoroid streams by active or dormant comets and asteroids, together with dynamical studies of meteoroids moving through the solar system. The study of meteoroids as space hazard is a topic of rapidly increasing interests due to the need of secure the safety and health of manned and unmanned space missions. It is also gaining impetus from the more ambitious initiative to build a human lunar outpost. Papers discussing optical techniques to observe meteor phenomena were prominent and results included the observation of enhanced activities of the 2006 Leonids and 2006 Orionids. The outcomes of years of infrasound and radar detections also showed that these methodologies are no longer stepchildren of meteor science, greatly expanding the mass range of extraterrestrial bodies which can now be studied. Radar meteor detection methodologies have evolved immensely since these instruments were first applied in the 1950s. Greater transmitted power, multi station interferometric techniques and the use of dual frequencies allow meteor radars to provide exciting new data, including the discovery of new meteoroid streams. In addition, in the past decade, the increasing use of high-power and large-aperture radars offer a new look at the meteor phenomena by allowing the routine study of the meteor head-echo, non-specular trails and a particle size range that bridge the historic gap between dust detector on board of satellites and specular meteor radars.

The second category of results included dynamical modeling exemplified by the power of reconstructing past meteor displays and accurate predictions of modern meteor stream activities. Meteor observations are now providing more precise input to fine-tune models, which is an achievement of increasing sophistication in both areas. For example, Comet Wild 2 data were preliminary explored for their relevance to cometary meteoroid properties. With the availability of this comet dust, interplanetary dust particles, micrometeorites and meteorites for laboratory studies, it is but a giant leap to use what we know of these samples as a starting point for experimental meteor science. Results from laboratory simulations of chemical releases during the meteor ablation process are showing that we are closer to understanding how the meteoric mass is deposited in the upper atmosphere. This particular advancement allows linking the meteoric flux with several aeronomical phenomena such as mesospheric metallic layers, noctilucent clouds and meteoric smoke particles embedded in the ionospheric plasma.

The scientific organizing committee (listed below) was responsible for shaping the meeting agenda covering both long-term research directions and objectives while also exploiting opportunities and testing new directions and interactions. These goals were achieved by judicious choices of invited, regular and poster presentations and are reflected in the compilation of articles presented in this book. The meeting also included an invited public lecture by Dr. Clark Chapman entitled “The hazard of asteroids and comets impacting Earth". We would like to take this opportunity to acknowledge and thank the long hours of hard work spent by the members of the local organizing committee (LOC, listed also below). The dedicated work of the LOC along with the tremendous help provided by students from the IEEC, Universitat Politècnica de Catalunya (UPC), Universitat de Barcelona (UB), IEEC, amateur astronomers volunteers and the support received from the CosmoCaixa museum staff resulted in a flawless meeting. This conference highlighted a growing multidisciplinary interest in meteorite, meteoroid and meteor research that we should nurture and also showed that results from this field can provide clues to address unanswered questions in other disciplines (i.e. aeronomy). We look forward to the next Meteoroids conference that will be held in the USA in 2010.

We would like to acknowledge the sponsors for this conference, including the *Ministerio de Educación y Ciencia* (MEC), IEEC-CSIC, and CosmoCaixa. Their financial contributions made it possible to have a successful and exciting scientific meeting and to prepare this tangible record of this proceedings volume.

The papers in this volume underwent the rigorous refereeing process that is applied to other papers in the journal Earth, Moon, and Planets. It could not have been achieved without the time and effort from over 100 referees, who guarded both scientific quality and clarity of the manuscripts. The guest editors of this volume acknowledge the professionalism and diligence of the editorial staff at Springer Science. It really requires all parties to cooperate to turn an idea into a proceedings volume. We also thank the editors and staff of Earth, Moon, and Planets.

Sincerely,
Josep M. Trigo-Rodriguez
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Chapter 1. Meteor Shower Activity, Forecasting, Dust Orbits

The IAU Meteor Shower Nomenclature Rules

Peter Jenniskens

Originally published in the journal Earth, Moon, and Planets, Volume 102, Nos 1–4.
DOI: 10.1007/s11038-007-9155-5

Abstract The International Astronomical Union at its 2006 General Assembly in Prague has adopted a set of rules for meteor shower nomenclature, a working list with designated names (with IAU numbers and three-letter codes), and established a *Task Group for Meteor Shower Nomenclature* in Commission 22 (Meteors and Interplanetary Dust) to help define which meteor showers exist from well defined groups of meteoroids from a single parent body.

Keywords Meteor shower · Meteoroid stream · Nomenclature

1 Introduction

Commission 22 of the International Astronomical Union is concerned with all aspects of meteors and with interplanetary dust. It falls under IAU Division III (Planetary Systems Sciences) and is currently chaired by Dr. Pavel Spurny of Ondrejov Observatory.

The International Astronomical Union has the task to define astronomical terms and give names to entities in space whenever needed to further astronomical research. Most recently, it labored over a definition of “planet” and created a category of “dwarf planets” to which Pluto belongs. Until now, meteor showers have not been named officially, as a result of which there is much confusion in the literature. Some showers are well defined but have multiple names (e.g., Draconids, gamma-Draconids, October Draconids, Giacobinids, Giacobini-Zinnerids), sometimes changing name when the radiant moves into another constellation. Many other showers are only ill defined and are given a different name in each new detection, often leaving us confused about whether these proposed showers are indeed groups of meteoroids from the same parent body.

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J.M. Trigo-Rodriguez et al. (eds.), *Advances in Meteoroid and Meteor Science.*
DOI: 10.1007/978-0-387-78419-9_2

During the IAU General Assembly in Prague on August 24, 2006, Commission 22 established a new *Task Group for Meteor Shower Nomenclature*, confirmed at the subsequent Division III meeting, with the objective to formulate a descriptive list of established meteor showers that can receive official names during the next IAU General Assembly in Rio in 2009. The objective of this action is, based on our community's work on meteor showers, to uniquely identify all existing showers. This would enable, for example, studies of associations between meteor showers and potential parent bodies among the many Near-Earth Objects that are being discovered.

Current members of the Task Group are Peter Jenniskens (chair), Pavel Spurny (president of C22), Vladimir Porubcan (head of the IAU Meteor Orbit Data Center), Juergen Rendtel (president of the International Meteor Organization), and regional representatives Tadeusz Jopek (Poland), Shinsuke Abe (Japan), Jack Baggaley (New Zealand), and Bob Hawkes (Canada).

To reach this goal, the traditional meteor shower nomenclature practices were formalized (with a few choices made to clean things up) by adopting a set of nomenclature rules, and a two-step approach was taken to uniquely identify meteor showers. First, a Working List of ~230 showers was adopted that gives a summary of showers reported until now from a compilation of past publications (Jenniskens 2006). To facilitate identification, the list is fully cross-referenced by giving the mean orbit and radiant from each prior record, as well as the source of the work.

Each proposed shower was given a name, as well as a unique number and a three-letter code to be used in future publications that discuss the recovery of the stream in orbit surveys and other types of observations. The IAU numbers go back to a system of numbers introduced in the work at the Harvard Smithsonian Center for Astrophysics and now used by the IAU Meteor Orbit Data Center, by simply adding to the numbers given to potential meteor showers in the past. The three-letter code is based on the codes used by IMO, with few exceptions. The designated names are mostly traditional, adhering to a system of nomenclature rules given below, but accepting that it is not always known what is the nearest star to the radiant position at the time of the peak of the shower.

The task ahead is to collect information to add more showers to this Working List, and to collect sufficient information for each shower to establish that the streams of meteoroids responsible are *groups of meteoroids from the same parent body*. The established showers will then be included in an IAU List of Established Meteor Showers, and will be voted on at the Commission 22 meeting in Rio for official recognition.

2 Meteor Shower Nomenclature

The general rule is that a meteor shower (and a meteoroid stream) should be named after the then current constellation that contains the radiant, specifically using the possessive Latin form (Table 1). The possessive Latin name for the constellations end in one of seven declensions:

-ae (e.g., Lyrae),
-is (e.g., Leonis),
-i (e.g., Ophiuchi),
-us (e.g., Doradus),
-ei (e.g., Equulei),
-ium (e.g., Piscium), or
-orum (e.g., Geminorum).

Table 1 Latin possessive names of meteor showers

Constellation	Latin possessive	Shower	Constellation	Latin possessive	Shower
Andromeda	Andromedae	Andromedid	Leo	Leonis	Leonid
Antlia	Antliae	Antliid	Leo Minor	Leonis Minoris	Leonis Minorid
Apus	Apodis	Apodid	Lepus	Leporis	Leporid
Aquarius	Aquarii	Aquariid	Libra	Librae	Librid
Aquila	Aquilae	Aquilid	Lupus	Lupi	Lupid
Ara	Arae	Arid	Lynx	Lyncis	Lyncid
Aries	Arietis	Arietid	Lyra	Lyrae	Lyrid
Auriga	Aurigae	Aurigid	Mensa	Mensae	Mensid
Bootes	Bootis	Bootid	Microscopium	Microscopii	Microscopiid
Caelum	Caeli	Caelid	Monoceros	Monocerotis	Monocerotid
Camelopardalis	Camelopardalis	Camelopardalid	Musca	Muscae	Muscid
Cancer	Cancri	Cancrid	Norma	Normae	Normid
Canes Venatici	Canum Venaticorum	Canum Venaticid	Octans	Octantis	Octantid
Canis Major	Canis Majoris	Canis Majorid	Ophiuchus	Ophiuchi	Ophiuchid
Canis Minor	Canis Minoris	Canis Minorid	Orion	Orionis	Orionid
Capricornus	Capricorni	Capricornid	Pavo	Pavonis	Pavonid
Carina	Carinae	Carinid	Pegasus	Pegasi	Pegasid
Cassiopeia	Cassiopeiae	Cassiopeiid	Perseus	Persei	Perseid
Centaurus	Centauri	Centaurid	Phoenix	Phoenicis	Phoenicid
Cepheus	Cephei	Cepheid	Pictor	Pictoris	Pictorid
Cetus	Ceti	Cetid	Pisces	Piscium	Piscid
Chamaeleon	Chamaeleontis	Chamaeleontid	Piscis Austrinus	Piscis Austrini	Piscis Austrinid
Circinus	Circini	Circinid	Puppis	Puppis	Puppid
Columba	Columbae	Columbid	Pyxis	Pyxidis	Pyxidid
Coma Berenices	Comae Berenices	Comae Berenicid	Reticulum	Reticulii	Rectuliid
Corona Australis	Coronae Australis	Coronae Australid	Sagitta	Sagittae	Sagittid
Corona Borealis	Coronae Borealis	Coronae Borealid	Sagittarius	Sagittarii	Sagittariid
Corvus	Corvi	Corvid	Scorpius	Scorpii	Scorpiid
Crater	Crateris	Craterid	Sculptor	Sculptoris	Sculptorid
Crux	Crucis	Crucid	Scutum	Scuti	Scutid
Cygnus	Cygni	Cygnid	Serpens	Serpentis	Serpentid
Delphinus	Delphini	Delphinid	Sextans	Sextantis	Sextantid
Dorado	Doradus	Doradid	Taurus	Tauri	Taurid
Draco	Draconis	Draconid	Telescopium	Telescopii	Telescopiid
Equuleus	Equulei	Equuleid	Triangulum	Trianguli	Triangulid
Fornax	Fornacis	Fornacid	Triangulum Australe	Trianguli Australis	Trianguli Australid
Gemini	Geminorum	Geminid	Tucana	Tucanae	Tucanid
Grus	Gruis	Gruid	Ursa Major	Ursae Majoris	Ursae Majorid
Hercules	Herculis	Herculid	Ursa Minor	Ursae Minoris	Ursae Minorid
Horologium	Horologii	Horlogiid	Vela	Velorum	Velorid
Hydra	Hydrae	Hydrid	Virgo	Virginis	Virginid
Hydrus	Hydri	Hydrusid	Volans	Volantis	Volantid
Indus	Indi	Indid	Vulpecula	Vulpeculae	Vulpeculid
Lacerta	Lacertae	Lacertid	–	–	–

Custom is to replace the final suffix for “-id”, or plural “-ids”. Meteors from Aquarius (Aquarii) are Aquariids, not Aquarids. An exception is made for meteors from the constellation of Hydrus, which will be called “Hydrusids”, in order not to confuse with meteors from the constellation of Hydra.

When the constellation name has two parts, only the second declension is to be replaced by “id”. Hence, meteors from Canes Venatici (Canum Venaticorum) would be “Canum Venaticids”.

When two constellations are grouped together, a dash is used and both constellation names will have “id”. Hence, Puppids-Velids. As a guideline, the sequence of those constellations are best in the order of which the radiants travel through them (Bootids-Coronae Borealids, not Coronae Borealids-Bootids). “Complex” can be used to indicate groups of meteor showers that may originate from the same (former) parent body, while groups of parent body fragments are usually referred to as a “family” (like the Hirayama families in the asteroid belt). Hence, one could say that the Taurid Complex of meteor showers originated from the Encke family of comets.

If higher precision is needed, then the shower is named after the nearest (if in doubt: brightest) star with a Greek letter assigned, as first introduced in the Uranometria atlas by Johann Bayer (1603), or one with a later introduced Roman letter. If in doubt, the radiant position at the time of the peak of the shower (in the year of discovery) should be taken. Hence, the meteors of comet IRAS-Araki-Alcock would be named “eta Lyrids” (or “eta-Lyrids”).

Following existing custom, one may add the name of the month to distinguish among showers from the same constellation. In this case, one could call the shower from comet IRAS-Araki-Alcock the “May Lyrids”, in order to differentiate from the more familiar “April Lyrids”.

For daytime showers, those with a radiant less than 32 degrees from the Sun, it is custom to add “Daytime”, hence the name for the “Daytime Arietids” in June as opposed to the Arietids in October.

South and North refer to “branches” of a shower south and north of the ecliptic plane, resulting from meteoroids of the same (original) parent body. Because they have nearly the same longitude of perihelion at a given solar longitude (the argument of perihelion and longitude of ascending node differing by 180 degrees between South and North), the two branches are active over about the same time period.

If the meteoroid stream is encountered at the other node, it is customary to speak of “twin showers”. The Orionids and eta-Aquariids are twin showers, even though each represent dust deposited at different times and are now in quite different orbits. As a matter of custom, twin showers and the north and south branches of a stream carry different names.

Meteor showers are not to be named after their parent bodies (e.g., Giacobinids, IRAS-Araki-Alcockids). The names of comets tend not to be Latin, making the naming not unique. Also, comet names can change when they get lost and are recovered. I like to add that even the proposed association may change, as many Taurids may originate from other parent bodies than 2P/Encke, for example.

In case of confusion, the *Task Group for Meteor Shower Nomenclature* will choose among possible alternative names, in order to establish a unique name for each meteor shower (e.g., eta-Lyrids, not May Lyrids).

3 The Working List

The Working List of Meteor Showers and the nomenclature rules were published in IAU Bulletin 99 (January 2007) and are posted at:

the website of the IAU Meteor Data Center: http://www.astro.sk/~ne/IAUMDC/
the website of IAU Commission 22 (Task Group for Meteor Shower Nomenclature): http://meteor.asu.cas.cz/IAU/nomenclature.html
IAU Information Bulletin January 2007: http://www.iau.org/fileadmin/content/IBs/ib99.pdf

During the Meteoroids 2007 conference in Barcelona, the Task Group convened and worked out the logistics of adding new streams to the Working List and adding new information on streams already in the Working List.

The institute responsible for maintaining the Working List is the *IAU Meteor Data Center*, which is currently managed by Vladimir Porubcan. The person responsible for setting up a website to facilitate the reporting of new streams and new data on existing streams, and give out new IAU numbers, will be *Tadeusz Jan Jopek* of Poznan Astronomical Observatory in Poznan, Poland:

http://vesta.astro.amu.edu.pl/Staff/Jopek/

The International Meteor Organization will take a role in coordinating the reporting of newly discovered streams by amateur meteor observers, mostly to facilitate the inclusion of streams that are only recognized from visual observations of meteor outbursts.

Once a website is in place that can provide updates to the Working List, newly discovered streams should not be reported in the literature without a designated IAU number. Before publication, the IAU MDC (Jopek) should be contacted to obtain a shower number. This will facilitate subsequent discussion in the literature to help confirm the detection. In the near future, it is the intention of the Task Group that a telegram be issued (CBET) with a brief summary of each new find to signify publication of the discovery as part of the process of reporting new streams, and in order to allert the community that new streams have been reported.

4 The List of Established Meteor Showers

In two years from now, in January of 2009, half a year before the next IAU General Assembly in Rio de Janeiro (Brasil), a subset of all showers will be selected for inclusion in the List of Established Meteor Showers. Selection will be based on the work in our community up to that point. The proposed list of established meteor showers will be posted prior to the General Assembly to facilitate discussion on whether there is sufficient evidence to include each shower in this list based on information and sources listed in the Working List. Only those showers that are beyond reproach are expected to pass the vote for official recognition during the Commission 22 meeting at the Assembly, and henceforth be recognized as a unique astronomical entity.

Note added in proofs The website for reporting new meteor showers is now operational at: http://www.astro.amu.edu.pl/~jopek/MDC2007/. An announcement was made on CBET 1088 (Sep. 25, 2007).

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Current Status of the Photographic Meteoroid Orbits Database and a Call for Contributions to a New Version

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Originally published in the journal Earth, Moon, and Planets, Volume 102, Nos 1–4.
DOI: 10.1007/s11038-007-9167-1

Abstract A central depository for meteor orbits obtained by photographic techniques, as a part of the IAU Meteor Data Center, was moved to the Astronomical Institute of the Slovak Academy of Sciences in Bratislava in 2001. The current version of the catalogue contains data on 4581 meteor orbits obtained by 17 different stations or groups from the period 1936 to 1996. Since 1996 a few huge campaigns were organised including very successful Leonids and Perseids. That is why we would prepare a new more complete version of the database. The main aim of this paper is a call to the observers of meteors having new or recalculated/remeasured data on photographic meteors to send them to the MDC, where after a check and consultations with the observer, the orbits will be included in the database.

Keywords Astronomical databases · Photographic meteor orbits

1 Current Version of Photographic Meteor Orbits Database

The IAU Meteor Data Center in Lund, since it was founded early in the 1980's, has acted as a central depository for meteor orbits obtained by photographic, video and radar techniques. It accumulated a huge number of meteoroid orbits obtained world-wide and is providing them to meteor scientists for various analyses.

In 2001, after Kiruna meteoroids conference, the IAU Meteor Data Center was moved to the Astronomical Institute of the Slovak Academy of Sciences in Bratislava. The database is covering an interval of 60 years—since 1936 when it became possible to determine precise photographic meteor orbits. In Fig. 1 the distribution of 4581 photographic meteors of the database observed over the year is depicted. The majority of well known streams are easily identified. The most populated streams in the database are the Perseids in August and Geminids in December.

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J.M. Trigo-Rodriguez et al. (eds.), *Advances in Meteoroid and Meteor Science.*
DOI: 10.1007/978-0-387-78419-9_3

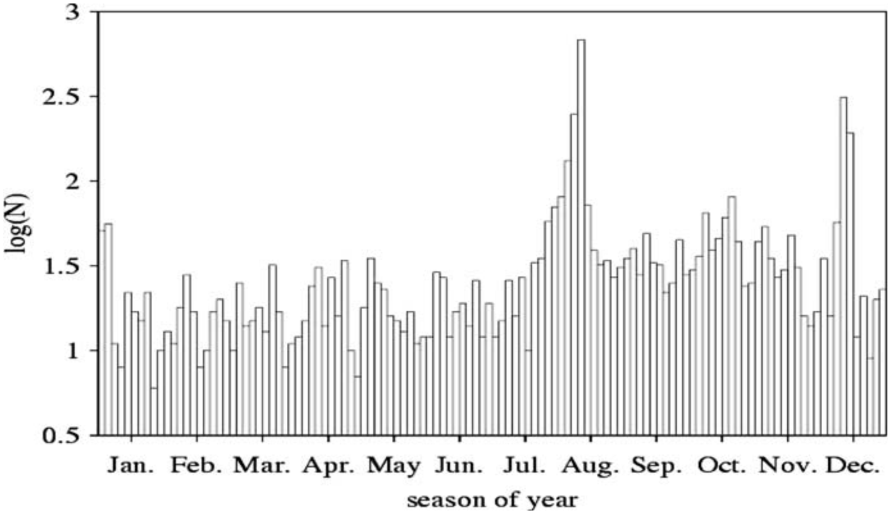

Fig. 1 Distribution of the 4581 photographic meteors of the IAU MDC database

Not only classical photography but also modern optical techniques are used now. It is very pleasant to follow that new catalogues listing meteor orbits detemined by video techniques are published, e.g. catalogue compiled by Koten et al. (2003) containing 817 orbits. The optical meteors cover a wide range of initial particle sizes, from fireballs having masses of 0.1–10 kg to faint TV meteors of the order of 10^{-7} kg. This article deals only with the classical photographic records compiled originally for the IAU Meteor Data Center in Lund (a series of the papers, e.g. Lindblad 1987 and 2001) and completed by additional meteor orbits published mainly by Spurny, Babadzhanov et al. and Halliday et al. The references in detail are published in Lindblad et al. (2005).

The previous versions of the database contained orbital and geophysical data on meteors in two separate files. The separation was mainly due to limitations of computer-memory capacity in the past. Because of a compatibility of the data with the old programs, we still conserved their two-file format in the last version of the database. At the same time, we introduced a new format and wrote the data into a single file named as *all2003.dat.* This merging of the data is not only more comfortable for their reading, but in various studies it is often necessary to utilize the complete information available for each meteor compiled in both original files (orbital—orbital elements; geophysical—radiants, geocentric and heliocentric velocities, etc.). Therefore, the new file contains the merged geophysical and orbital data (in ASCII format) sorted by the date of meteor detection, from January 1 to December 31. A five-line format for each meteor is chosen to provide a comfortable reading of the complete data in one place. A blank line separates the data of two neighbouring meteors. All the values are expressed in full figures. If a given parameter was not published by the original author then zeros are inserted in the file (to enable a formated reading, too). In *all2003.dat* file, all the orbital data are calculated by us by the same procedure, on the basis of the published time of appearance, the radiant position and geocentric velocity. In all of the published data catalogues, except for the MORP (Halliday et al. 1996) and Betlem et al. (1998) orbits, the 1950 equinox was used. In this version we converted the angular elements to J2000.0.

Eccentricities of some meteor orbits in the database considerably exceed unity. A limit of the heliocentric velocity of about 48 km s^{-1} can be regarded as a reasonable limiting value between acceptable and unacceptable heliocentric velocities (Lindblad et al. 2005). We recommend to omit 46 meteors with the heliocentric velocity over this limit from all statistical studies.

The photographic database version 2003, can be downloaded from the IAU MDC at the Astronomical Institute of the SAS from the address: http://www.astro.sk/~ne/IAUMDC/Ph2003/database.html

Available are the geophysical and orbital data on 4581 photographic meteors (ASCII format) sorted as in the original catalogues of the individual authors or stations. The *all2003.dat* file contains the merged geophysical and orbital data.

Besides the three data files listed above, there are at disposal lists of 875 Perseids and 387 Geminids meteoroid streams members selected from the database (Svoren and Kanuchova 2005; Kanuchova and Svoren 2006).

2 Preparation of the Next Version

To detect and resolve any inconsistencies in the orbital data we will recalculate all the obtained orbits based on the position of corrected radiant and geocentric velocity at the time of meteor observation. The IAU meteor database contains geophysical parameters and orbital elements, which are mutually dependent. Therefore, one data set can be used to verify the correctness of the other. To check the consistency of the two data sets, the following two recalculations are made:

(1) Assuming that the published radiant coordinates and geocentric velocity of the meteor at the time of detection were correct, the orbital elements q, e, ω, Ω and i are recalculated.

(2) However, it is obvious that errors sometimes appear also in the published geophysical (encounter) data. Hence we consider the five published orbital elements as the input and recalculate the radiant coordinates α, δ and the geocentric velocity V_g of the meteor. In this recalculation the most optimal method of theoretical radiant prediction for a given orbital geometry (Neslusan et al. 1998) is used.

3 Call for New Observed or Recalculated Observations

The IAU MDC catalogue summarizes photographic meteor orbits observed only until 1996. However, since 1996 more very successful observing campaigns were organised and new meteor orbits were obtained, including very successful observations of the Leonids and Perseids. This is a great motivation to update and prepare a new more complete version of the database. The main aim of this paper is a call to observers of meteors having new or remeasured data of photographic meteors to send them to the MDC. After a check and consultations with the observer, the orbits will be included in the database.

For the future we plan to introduce a new service. Each observer or contributor to the database will be able to perform a preliminary check of the consistency of his own geocentric and orbital data sets before he sends the data to us, by on-line calculator, anonymously.

We plan also a small change in the format of the database. Data, if possible, will be published together with their error bars. Errors could be obtained from the original reports of the observers based on precision of observable techniques and methods used. A comparison of precision of individual groups and stations could be a second way to calculate them. We would like to avoid an inclusion of the errors obtained formally from different statistical processes.

Acknowledgements The authors are indebted to K. Ohtsuka for his collaboration in checking of the published data. This research was supported by VEGA - the Slovak Grant Agency for Science (Grants Nos. 1/3067 and 2/7009).

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The Dynamics of Low-Perihelion Meteoroid Streams

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Originally published in the journal Earth, Moon, and Planets, Volume 102, Nos 1–4.
DOI: 10 1007/s11038-007-9182-2

Abstract The Canadian Meteor Orbit Radar (CMOR) has collected information on a number of weak meteor showers that have not been well characterized in the literature. A subsample of these showers (1) do not show a strong orbital resemblance to any known comets or asteroids, (2) have highly inclined orbits, (3) are at low perihelion distances ($\ll 1$ AU) and (4) are at small semimajor axes (<2 AU). Though one might conclude that the absence of a parent object could be the result of its disruption, it is unclear how this relatively inaccessible (dynamically speaking) region of phase space might have been populated by parents in the first place. It will be shown that the Kozai secular resonance and/or Poynting–Robertson drag can modify meteor stream orbits rapidly (on time scales comparable to a precession cycle) and may be responsible for placing some of these streams into their current locations. These same effects are also argued to act on these streams so as to contribute to the high-ecliptic latitude north and south toroidal sporadic meteor sources. There remain some differences between the simple model results presented here and observations, but there may be no need to invoke a substantial population of high-inclination parents for the observed high-inclination meteoroid streams with small perihelion distances.

Keywords Meteoroid stream · Poynting–Robertson drag · Secular resonance · Toroidal meteor sources · Meteor shower · Sporadic meteors

We report here on a number of meteor showers that have been recently studied by means of the Canadian Meteor Orbit Radar (CMOR, Jones et al. 2005). These showers are weak to moderate in strength and were either discovered in the CMOR catalogue (Brown et al. 2007) or have only been poorly characterized in previous studies. In Sect. 1, those showers with clear links to parent bodies are discussed. Section 2 deals with links to other better-known showers, and Sect. 3 examines the dynamics of this ensemble of streams and its possible link to the toroidal sporadic meteor sources.

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J.M. Trigo-Rodriguez et al. (eds.), *Advances in Meteoroid and Meteor Science.*
DOI: 10.1007/978-0-387-78419-9_4

1 Links with Parent Objects

One new shower has a clear connection to a parent. The Daytime ε Perseids shower has an orbit which bears a similarity to that of comet 96P/Machholz. Table 1 lists their respective orbital elements. The Drummond (1981) D' of this association is 0.14 and the Valsecchi et al. (1999) D is 0.047 though the D of Southworth and Hawkins (1963) is somewhat larger at 0.435. There is a strong resemblance in the perihelion distance q, inclination i and longitude of the ascending node Ω. The match is poorer in the semimajor axis a (which is difficult to measure) and the argument of perihelion ω, possibly due to precession. We conclude that this shower is likely part of the Quadrantid meteor complex, to which 96P has been linked in the past (McIntosh 1990; Babadzhanov and Obrubov 1992; Gonczi et al. 1992; Jones and Jones 1993; Jenniskens 2004; Wiegert and Brown 2005).

2 Links with Known Streams

Some of the other weak showers detected by CMOR are related to the multiple intersections between a meteoroid stream and the Earth's orbit that occur during the stream's precession cycle. For example, the Daytime April Piscids and the South Daytime May Arietids (sometimes called the *o* Piscids in the literature) are both clearly related to the North and South *i* Aquariids (see Table 2). Under apsidal precession, the intersection points of this stream with the Earth's orbit can easily be computed to occur near values of the argument of perihelion ω of 50°, 130°, 230° and 310°. We have also verified this by numerical experiment. Thus the Daytime April Piscids and the South Daytime May Arietids, together with the N/S *i* Aquariids, complete the set of four separate showers produced by the precession of meteoroids released from a single parent.

3 The Remaining Streams

Despite the associations discussed in the two preceding sections, most of the weak showers in the CMOR catalog do not have immediately obvious parent bodies, nor clear links to known streams. In fact, many of these streams have semimajor axes a below 2 AU, perihelia q well inside Mercury's orbit, and high inclinations (Table 3 and Fig. 1), placing them in a region of phase space that is very sparsely populated by comets and asteroids. A search of the asteroid and comet databases turns up no bodies with orbits clearly similar to those of these streams.

One might speculate that the low-perihelion distances of these streams, together with the high activity levels and rapid depletion they would produce in a source comet, might account for the current absence of parent bodies. The parents would simply have disrupted or become inactive or extinct. However this would not explain how the source bodies

Table 1 Comparison of the orbits of 96P/Machholz (Marsden and Williams 2005) and the Daytime ε Perseids

Name	a (AU)	q (AU)	e	i (°)	Ω (°)	ω (°)
D ε Perseids	4.6 ± 1	0.13 ± 0.01	0.97 ± 0.01	63 ± 2	96 ± 0.3	40 ± 2
96P/Machholz	3.01	0.123	0.959	59.9	94.5	14.6

Errors for the shower elements are approximate

Table 2 The elements of the Daytime April Piscids and South Daytime May Arietids, together with those of the better-known North and South i Aquariids

Name	a (AU)	q (AU)	e	i (°)	Ω (°)	ω (°)
Daytime April Piscids	1.51	0.26	0.83	4.7	25	50
S Daytime May Arietids	1.51	0.27	0.82	5.1	227	232
N i Aquariids	1.52	0.27	0.83	5.7	159	309
S i Aquariids	1.55	0.22	0.86	5.3	309	134

The orbits are from the CMOR catalogue

Table 3 A selection of the new or previously little-studied meteor showers in the CMOR catalogue

Name	a (AU)	q (AU)	e	i (°)	Ω (°)	ω (°)
N Daytime ω Cetids	1.58	0.12	0.93	34	45	33
S Daytime ω Cetids	1.72	0.14	0.92	36	225	216
S June Aquilids	1.12	0.06	0.94	56	260	159
Daytime γ Taurids	1.57	0.10	0.93	23	266	211
Vulpeculids	0.76	0.17	0.77	55	105	335
N June Aquilids	1.71	0.11	0.94	39	101	328
β Equulids	0.89	0.16	0.82	50	106	330
July σ Cassiopeiids	1.09	1.00	0.08	81	105	217
ψ Cassiopeiids	2.14	0.93	0.56	83	118	141
N δ Aquariids	1.81	0.10	0.95	24	139	329
σ Serpentids	1.92	0.16	0.92	64	276	41
ω Serpentids	1.37	0.16	0.88	56	276	39
θ Coronae Borealids	1.11	0.92	0.17	77	296	125
λ Bootids	1.49	0.96	0.36	79	295	207
ζ Coronae Borealids	2.34	0.82	0.65	80	294	125
α Antilids	2.47	0.14	0.94	64	136	140

reached these orbits in the first place, as the dynamical evolution of bodies into this region is slow.

We report here that Poynting–Robertson (PR) drag is likely responsible for the current orbits of these showers. It will be shown that streams produced by comets at larger a and q can evolve into streams of the type described above (or at least the smaller members of these streams can) on time scales of only thousands of years, short compared to their precession times.

Additionally, we report that many such streams are trapped in the Kozai resonance (Kozai 1962) which causes their eccentricities e and inclinations i to oscillate. Such meteoroids produce radiant distributions with some of the characteristics of the toroidal sporadic meteor sources.

3.1 Investigations

In order to study the dynamics of these streams, the showers in Table 3 were simulated numerically with a symplectic Wisdom and Holman (1991) style integrator able to handle

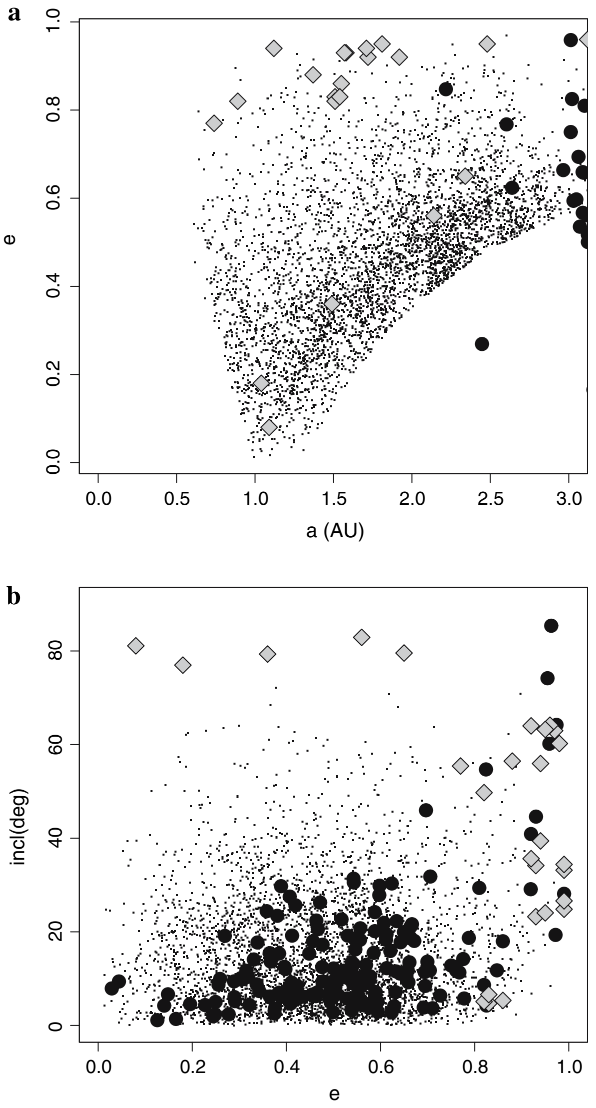


Fig. 1 The orbital distributions of near-Earth asteroids (dots, from the AstDys website http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo), comets (black circles, Marsden and Williams (2005)) and the showers discussed here (grey diamonds) in (**a**) *a*–*e* and (**b**) *e*–*i* space

close encounters by the hybrid method (Chambers 1999). Two sets of ten particles were spread along the orbit of each meteoroid stream at equal intervals of mean anomaly. One set was assigned a beta of zero for comparison purposes. The other set was assigned a β value of 0.0057 to simulate particles of a density of 2,000 kg m^{-3} and a radius of 100 μm (Weidenschilling and Jackson 1993). Each set was integrated backwards for 50,000 years with a time step of one day.

The simulation of multiple particles per stream allows us to better understand the effects of differential perturbations such as planetary encounters. However, these simulations have only a small number of particles and are not of the caliber of those frequently used these days for detailed shower timing and strength predictions, which may involve tens of thousands or more particles. Nevertheless they provide great insight into the dynamical behaviour of these streams.

A common feature of the numerical simulations is a substantial change in the semimajor axes of the stream orbits over time. Some streams can undergo changes in a at rates exceeding 1 AU per 10^3 years, though average rates near 1 AU per 10^4 years are more typical. Thus the stream produced by a Jupiter family comet with $a \approx 3$ AU could become one with $a \sim 1$ AU (like many of the showers in Table 3) in only a few 1,000 years.

An example of the semimajor axis evolution of one such stream, the β Equulids, is shown in Fig. 2. Note how the particles with $\beta = 0.0057$ have rapidly changing semimajor axes while the control particles with $\beta = 0$ remain largely unaffected. This indicates that these changes are indeed the result of radiation forces. If the new showers discussed here are primarily composed of small particles, then they could have been released from comets with larger values of a and q and subsequently transported to their current orbits by PR drag. This might also explain the absence of these showers from visual shower catalogues, as such streams are unlikely to contain many of the larger meteors (with smaller β values) which are more easily observed by optical means.

Figure 3 shows the eccentricity evolution of the β Equulids stream. Notably absent is the monotonic circularization expected for meteoroids experiencing strong PR drag (Wyatt and Whipple 1950), though we note that a careful treatment by Breiter and Jackson (1998) revealed that there were cases where a small increase in e could be expected from PR drag. In the simulations presented here, e is seen to oscillate on time scales of 10^4 years. The reason that an alternation of e occurs rather than a simple reduction in its value is because of the action of the Kozai resonance (Kozai 1962), also known as the secular precession effect discussed by Babadzhanov and Obrubov (1987). This secular effect pumps angular momentum in and out of the meteoroid orbit faster than PR drag removes it, and thus controls the value of e in this dynamical regime.

The secular resonance that affects e also produces an oscillation in the inclination i. Its effect on the β Equulids stream is shown in Fig. 4. Inclination and eccentricity oscillate out of phase with each other, and the meteoroids spend much of their time at high inclination,

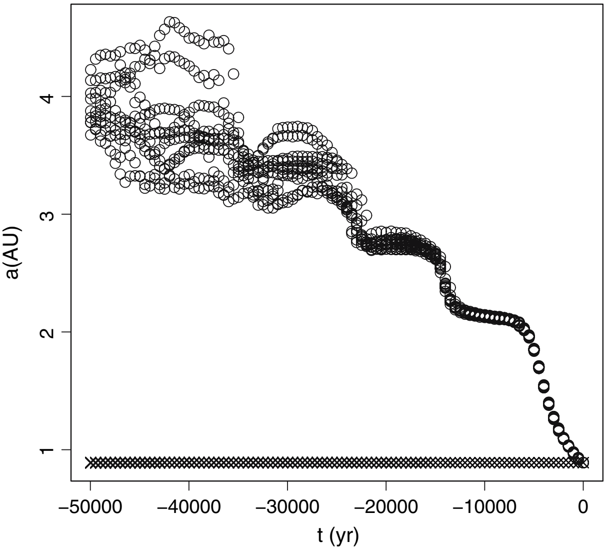
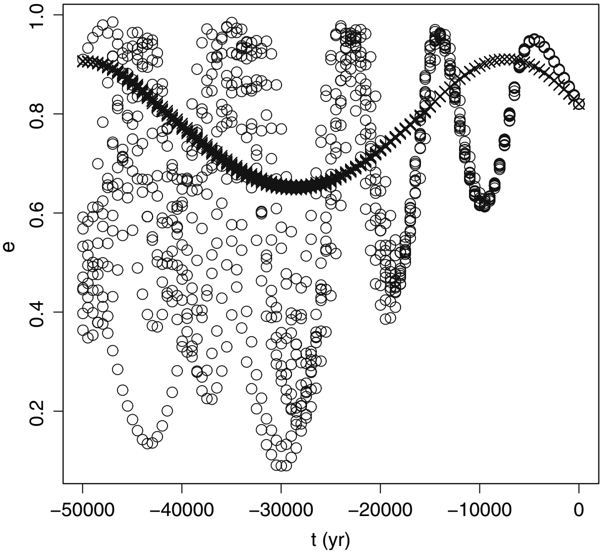


Fig. 2 The evolution of the semimajor axis of the β Equulids meteoroids simulated backwards for 50,000 years. The open circles are 100 µm radius particles ($\beta = 0.0057$), while the crosses are particles with $\beta = 0$

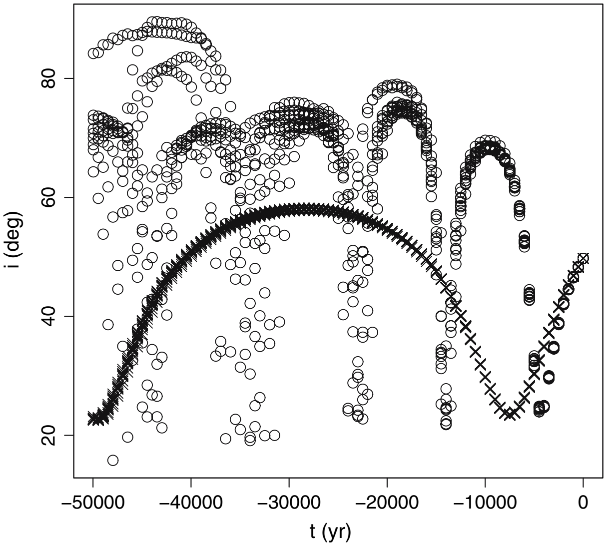
Fig. 3 The evolution of eccentricity of the β Equulids meteoroids simulated backwards for 50,000 years. See Fig. 2 for more details



at a time-average value near 60°. Thus meteoroid streams produced at much lower inclination ($\lesssim 20°$) can be driven up to much higher inclination ($> rsim 80°$) by this effect. In fact, these particles spend most of their time at high inclination. This result is relatively insensitive to β, even particles at $\beta = 0$ also have large time-averaged inclinations. Thus, there is no need to invoke a substantial population of high-inclination parents for these streams; they could easily be produced by bodies with a much flatter distribution (e.g. the Jupiter-family comets) pumped up by the secular resonance.

The high time-averaged inclination of these meteoroids also suggests a connection with the north and south toroidal sporadic sources that we investigate next.

Fig. 4 The evolution of inclination of β Equulids meteoroids simulated backwards for 50,000 years. See Fig 2 for more details



3.2 The Toroidal Sporadic Meteor Sources

The orbital element distributions of the north toroidal sporadic source have been determined (e.g. Jones and Brown 1993), and it is expected that those of the southern toroidal source will be similar. However, the origin of the meteors that produce these sources is not known. The elements presented in Jones and Brown (1993) for the northern source show a peak in a at 1 AU, one in inclination near 60°, and a distribution in e with a preponderance of near-circular orbits. The high-inclination is particularly puzzling owing to the absence of comets or asteroids on such orbits. Could the high inclination showers discussed here be connected to the toroidal sporadic sources? Perhaps as these meteoroids diffuse away from the shower orbits and drift inwards under PR drag, many remain in the secular resonance at high i, ultimately becoming toroidal sporadics?

In order to investigate this possibility, we simulated meteoroid streams originating from hypothetical parents of the high-i streams described above. The difference between these simulations and the ones mentioned earlier are (1) these simulations are run forwards in time, (2) three different particle radii are included: 50, 100 and 200 μm (10 particles each, with appropriate β values) and (3) the meteoroid streams are started with the elements given in Table 3 with the exception that the semimajor axis is set to 3 AU. This provides a proxy for the putative cometary parents of these streams, here assumed to be Jupiter-family comets. By simulating these streams forwards under PR drag, we can make a rough determination of whether or not the meteoroids produced by such parents could produce the toroidal sporadic sources.

Figure 5 shows the resulting density of radiants of the simulated meteoroids with nodes within 0.1 AU of the Earth over 10^5 years (roughly their collisional lifetime (Grun et al. 1985), though their high inclinations are likely to prolong their survival in practice, weighted according to their collision probability with the Earth (from Opik (1951) as given by Galligan and Baggaley (2004)). The radiants are based on the true minimum approach distance between the orbits, not just the distance between the nodes. The radiants are

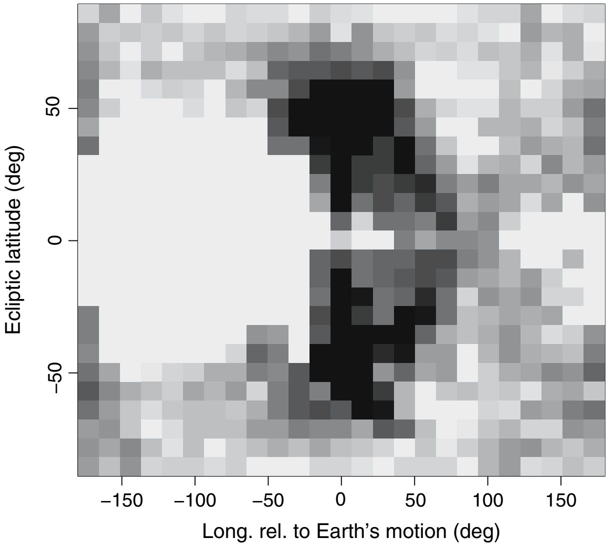


Fig. 5 The radiant distribution of simulated meteoroids weighted according to the collision probability with the Earth. Darker tones indicate a higher density of meteor radiants. The Earth's apex is towards the origin in this plot and the Sun is at a relative longitude of −90°

determined simply from the relative velocity of the meteoroid and the Earth at closest approach.

Both north and south toroidal radiants are reproduced, though they are nearer the ecliptic plane than the observed toroidal radiants which are at ecliptic latitudes of ±60° (Jones and Brown 1993). The orbital distributions of meteors within the toroidal radiant will be examined next. The orbits will be found to bear some resemblance to observed toroidal meteors, but this scenario probably does not provide a complete explanation of the origin of the toroidal sources.

Figure 6 shows the distribution of inclinations within the radiant area defined by a longitude relative to the apex of less than 30° and a latitude (either north or south) between

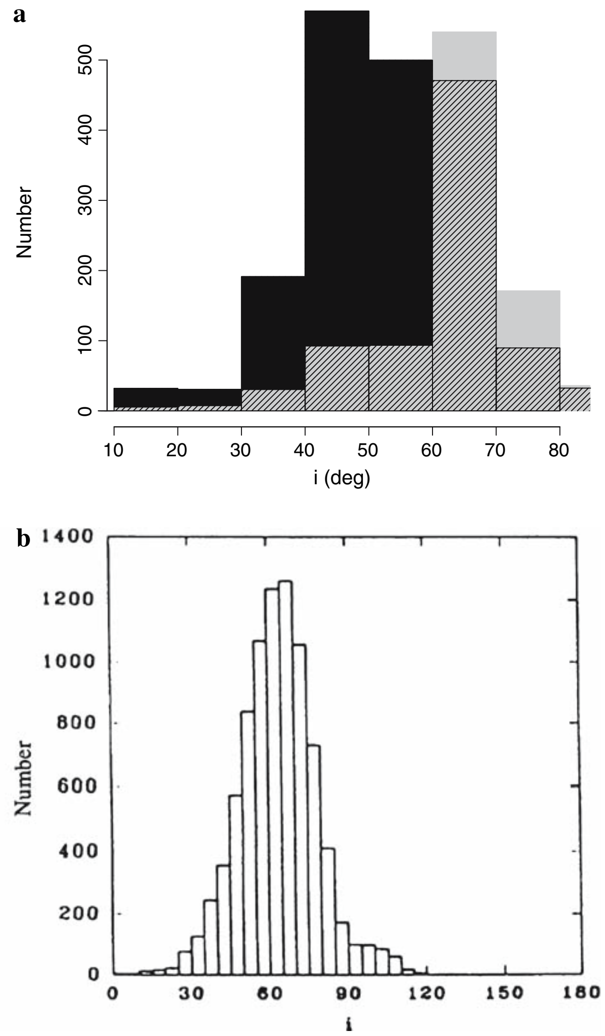


Fig. 6 (**a**) The distribution of the inclinations of simulated meteoroids accumulated over 10^5 years. The histogram in grey is unweighted; the black is weighted according to the collision probability with the Earth, normalized to a similar peak value. Panel (**b**) is the observed distribution of north toroidal source meteors from Jones and Brown (1993)

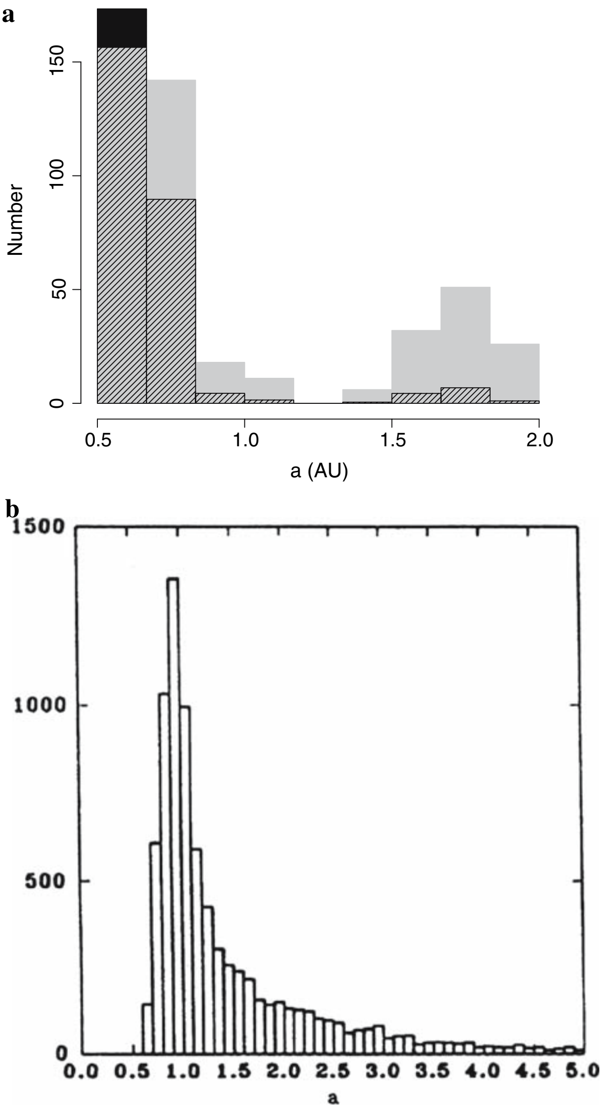


Fig. 7 The distribution of semimajor axes of (**a**) simulated meteoroids and (**b**) observed north toroidal source meteors from Jones and Brown (1993). See Fig. 6 for more details

40° and 70°. The distribution shows a peak at high inclination, similar to that observed but not expected given our choice of radiant latitude. Figures 7 and 8 show the orbit element distributions for the semimajor axis and eccentricity for those meteoroids in the above radiants. The weighted distributions bear some resemblance the measured distributions for the north toroidal source, given in Fig. 9 of Jones and Brown (1993), but are not identical. The simulated semimajor axis distributions, both weighted and unweighted, are sharply peaked like the observations, but at values below those of the observed distribution. The simulated and observed eccentricity distributions differ as well. The observed distribution contains a preponderance of near-circular orbits. The unweighted simulated distribution is

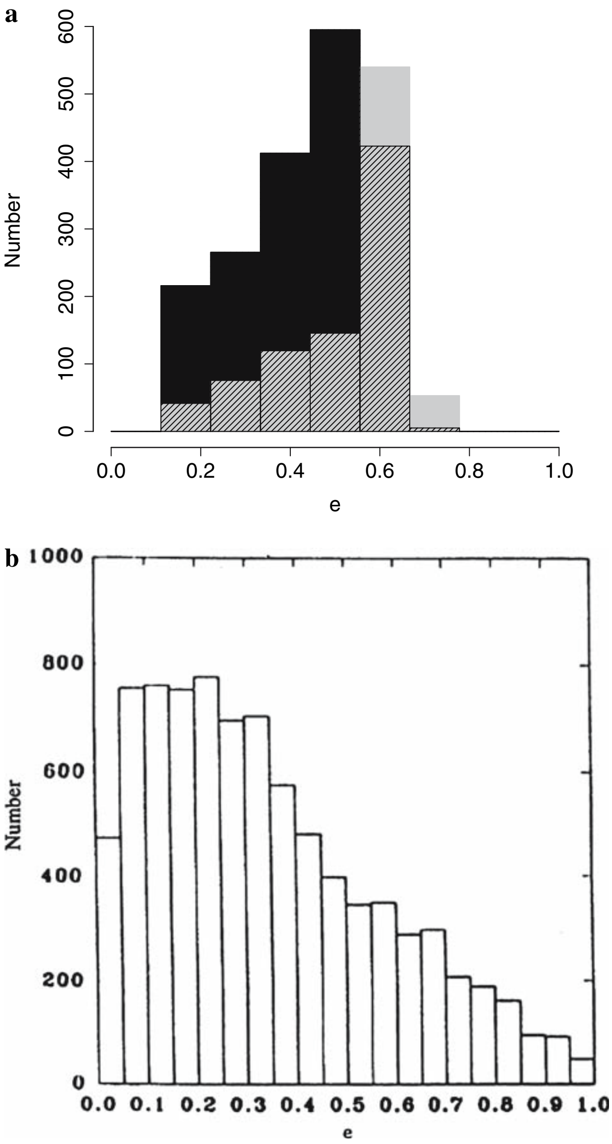


Fig. 8 The distributions of eccentricity of (**a**) simulated meteoroids and (**b**) observed north toroidal source meteors from Jones and Brown (1993). See Fig. 6 for more details

peaked near $e = 0.6$. Though the discrepancy is less pronounced for the weighted distribution (which should more closely match observations), the match is far from perfect. The differences between the experimental and theoretical distributions may simply be due to our coarse modelling of the parent streams. However, it probably also indicates that the crude scenario employed here, despite some intriguing intimations, is insufficient to completely explain the toroidal sporadic sources.