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Meteor cluster detection algorithm
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Front cover photo

Taurid fireball on 2013 September 14 at $05^{h}01^{m}$ UT, photographed from Observatorio del Teide, Izana, Tenerife using Canon EOS 20D camera at ISO 800 and $f/3.5$, $f = 8$ mm Peleng fish eye lens with exposure time 59 s. Photo courtesy: Jürgen Rendtel.

Writing for WGN This Journal welcomes papers submitted for publication. All papers are reviewed for scientific content, and edited for English and style. Instructions for authors can be found in WGN **31:4**, 124–128, and at `http://www.imo.net/docs/writingforwgn.pdf` .

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Janus—25 Years of the International Meteor Organization

Cis Verbeeck[1]

More than 25 years, almost as long as one revolution of 55P/Tempel-Tuttle. That's how long Jürgen Rendtel has served IMO as its first President. During this period, meteor science, observation methods, and the amount of available data have changed enormously, and several exciting events have occurred. Big advances were made in stream modeling just in time to predict the Leonid storms, meteorites of several imaged fireballs were recovered, including 2008 TC_3, a small NEO that was discovered barely a day before it impacted in Sudan (Jenniskens et al., 2009). And of course, the very well-documented airburst above the Russian city Chelyabinsk caused by a ~ 20 meter-sized body on the morning of February 15, 2013 (Brown et al., 2013). Even impacts on the Moon did not escape the attention of some meteor workers lately.

Throughout this time, Jürgen — together with the IMO Council — has guided IMO to be and remain an organization for all people interested in meteors. Since IMO's foundation in 1988, the organization has made many remarkable achievements: defined a global standard for visual observations, maintained a database of visual observations from all over the world, collected fireball reports, photographic, video, and telescopic data in a systematical way. IMO's observational databases caught the interest from the professional meteor community from the start, and nowadays several professional-amateur collaborations exist, while professionals attend IMCs and amateurs attend professional conferences. The impressive revolution that video observations have brought into meteor science in the last few years builds in large part on the intensive and sustained pioneering work that was performed within IMO from the early nineties onwards.

Many of these achievements are the collective effort of all IMO members, of which we can be proud. This has only been possible, though, thanks to the enormous efforts of IMO Commission Officers and Councillors and some other individuals who gather all the data, process and analyze it, write handbooks and papers, organize IMCs, develop and maintain the IMO website, edit IMO's journal WGN, and take care of all mailings, administrative and financial tasks, among many other things. On many occasions, difficult decisions had to be taken. It is at such times that the IMO Council performs one of its most important tasks: setting out the way in which they think IMO should be headed. Jürgen's kind, calm, and wise attitude has always been of great value for the Council's decisions.

It would take me too long to sum up what Jürgen has done for IMO and meteor science, but let me just mention a few aspects. Besides writing large parts of several editions of IMO's meteor handbooks and other publications, he has contributed a wealth of meteor papers to WGN and other journals, and has presented results obtained from IMO data at several professional conferences as well as at IMCs. Apart from observational analyses, Jürgen wrote important classics such as the 1990 Koschack & Rendtel (1990a; 1990b) papers that solved the problem of deriving meteoroid flux densities from visual observations.

Not only has he written papers, he has also edited WGN papers and IMC Proceedings, and has mailed countless IMO publications. If it would be a discipline for the Guinness World Records, he would be the winner in the category "having organized the most IMCs", on par with Paul Roggemans and Hans-Georg Schmidt. Jürgen has been involved in the Professional-Amateur Working Group and the Task Group on Meteor Shower Nomenclature, both established by the IAU Commission 22. He has been an avid visual and photographic observer since 1972 and was the most proficient visual observer worldwide for many years, amassing several hundred hours of effective observing hours per year. In more recent years, he has started video observations as well.

Last year, Jürgen decided not to run for President anymore, but I am happy to announce he will stay in the Council as Vice-President to ensure continuity. We are all much indebted to Jürgen's vast legacy as President. Thank you for everything, Jürgen, in name of all IMO members!

Rainer Arlt did not renew his term as IMO Councillor. As in Jürgen's case, our organization owes a lot to Rainer, who has led IMO's Visual Commission since 1994. He has entered vast amounts of visual meteor data into the Visual Meteor Data Base (VMDB) and set up rigorous checks to ensure the quality of these data. He has contributed to several editions of IMO's handbooks and has regularly written interesting, profound analyses of meteor shower activity, both for WGN and elsewhere. He has also developed the Radiant program (`http://www.imo.net/software/radiant`) which calculates density distributions of meteor radiants and has

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been invaluable over the years for determining meteor shower associations. Rainer has presented many inspiring talks at IMCs and professional conferences, is an editor for WGN, and has even been the journal's effective Editor-in-Chief ad interim for one year. He has mailed countless IMO publications and designed the current cover of WGN. These are just some of Rainer's contributions to IMO. As an IMO Councillor since 1998, Rainer has been of great help in defining and deciding new ideas and solutions. Here's a warm "Thank you!" to you, Rainer.

I am glad to welcome Jean-Louis Rault to the Council. Jean-Louis has been the Director of IMO's Radio Commission since 2007, and I am happy that he will help guide our organization as Councillor as well. Welcome to the Council, Jean-Louis!

In the recent Council elections, I was elected as IMO President. I would like to thank all voters for their support. As President, together with the other Council members, I will continue my dedication to monitor and foster our organization's health, both at present and in many years to come. Apart from solving problems and meeting challenges when they arise, a clear vision on our organization's mission and future will guide the Council to ensure the continued success of IMO. I invite all IMO members to join us in defining and implementing this vision of IMO. Do not hesitate to write me if you have any comments, questions, or suggestions about IMO.

I will invest in promoting meteor science and will continue close communication with many meteor enthusiasts. I will strive for smooth IMO operations, focusing on increased author participation in WGN, on the continuation of our tradition of outstanding IMCs, on improving the website, on continued fruitful collaboration with professionals, and on increased visibility of IMO and its products in order to serve the meteor community and attract new members and observers.

In brief, I want to invest in IMO as an organization for meteor workers, with active participation, involvement and consultation of its members, and to the benefit of their needs and the advancement of meteor science.

Happy New Year and clear skies!

References

Brown P. G., Assink J. D., Astiz L., Blaauw R., Boslough M. B., Borovicka J., Brachet N., Brown D., Campbell-Brown M., Ceranna L., Cooke W., de Groot-Hedlin C., Drob D. P., Edwards W., Evers L. G., Garces M., Gill J., Hedlin M., Kingery A., Laske G., Le Pichon A., Mialle P., Moser D. E., Saffer A., Silber E., Smets P., Spalding R. E., Spurny P., Tagliaferri E., Uren D., Weryk R. J., Whitaker R., and Krzeminski Z. (2013). "A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors". *Nature*, **503:7475**, 238–241.

Jenniskens P., Shaddad M. H., Numan D., Elsir S., Kudoda A. M., Zolensky M. E., Le L., Robinson G. A., Friedrich J. M., Rumble D., Steele A., Chesley S. R., Fitzsimmons A., Duddy S., Hsieh H. H., Ramsay G., Brown P. G., Edwards W. N., Tagliaferri E., Boslough M. B., Spalding R. E., Dantowitz R., Kozubal M., Pravec P., Borovicka J., Charvat Z., Vaubaillon J., Kuiper J., Albers J., Bishop J. L., Mancinelli R. L., Sandford S. A., Milam S. N., Nuevo M., and Worden S. P. (2009). "The impact and recovery of asteroid 2008 TC3". *Nature*, **458:7237**, 485–488.

Koschack R. and Rendtel J. (1990a). "Determination of spatial number density and mass index from visual meteor observations (I)". *WGN, Journal of the IMO*, **18:2**, 44–58.

Koschack R. and Rendtel J. (1990b). "Determination of spatial number density and mass index from visual meteor observations (II)". *WGN, Journal of the IMO*, **18:4**, 118–140.

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.*

Letter — Meteoroids, asteroids, and the professional-amateur collaboration

Detlef Koschny[1]

Last year began with a bang: On the morning of 2013 February 15, a large meteoroid – or a small asteroid, depending on which community you belong to – entered the Earth's atmosphere in Russia. It was about 20 m in size and ended its path in a so-called airburst close to the city of Chelyabinsk (Brown et al., 2013). Many windows were shattered, buildings were damaged, and over 1500 people were injured, mainly by breaking glass. Many meteorites have been recovered, with the largest piece recovered from the bottom of a lake, weighing several hundred kg.

This happened on the same day as the predicted flyby of asteroid 2012 DA_{14}, discovered a year before by the La Sagra Sky Survey, an amateur group searching for near-Earth asteroids from Southern Spain. At the very same day, a group of professionals presented a plan on how to react to an imminent asteroid impact threat to the United Nations in Vienna, which had been developed since about 2008.

Another bang – a bit smaller – started this year: The very first asteroid discovered in January, 2014 AA, was found to enter the Earth's atmosphere only a few hours after its detection. The announcement actually only went out after the hit. Peter Brown, from the University of Western Ontario, confirmed the atmospheric entry using data from infrasound sensors (Beatty, 2014). This object was estimated to be between 2 and 5 m in size, and probably only generated a very nice bright fireball – unfortunately somewhere over the Atlantic Ocean where nobody was there to see it.

All these events – and previous ones like the explosion of 2008 TC_3 over the Sudan (Jenniskens et al., 2009) or the crater-generating fireball in Carancas, Peru, in 2007 (Tancredi et al., 2009) – have raised the public and political awareness of the fact that natural objects from space do enter our atmosphere.

Previously the asteroid community worried about objects larger than 140 m – a size where they would do significant damage when encountering the Earth. In recent years this has changed, and we now acknowledge that also smaller objects merit attention. This has led to the installment of professional fireball and meteor networks, initially a field of mainly amateur astronomers. NASA's Meteoroid Office has started setting up camera stations in the mid-US using commercial video surveillance cameras with wide-angle lenses (Cooke & Moser, 2012). The CAMS network (Cameras for All-sky Meteor Surveillance; Johnson & Jenniskens, 2014) started operation just a few years ago in the Western US, using large clusters of surveillance cameras. The Paris Observatory has been granted funding to set up around 100 meteor cameras in France (Colas et al., 2012). Thus, good times for meteor observers!

Back to last year, when another noteworthy event happened in August: The International Meteor Conference and the Meteoroids 2013 conference to place back-to-back in Poznan, Poland. Many professionals enjoyed the relaxed atmosphere of the normally amateur-dominated IMC; and, vice-versa, many amateurs could get a glimpse of the professional work during the Meteoroids conference. To me in many areas the work is not so different – many amateurs deliver professional work, the only difference is that they don't get paid for it. And they are not required to publish their work.

Having said this, I realized that this is a shame – quite some good work from amateurs goes unnoticed because of this. I would thus urge amateurs who think that they do good work – write about it in WGN! WGN is easily accessible by amateurs and read by many professionals. And I urge professionals: Look at the work the 'amateurs' do, and involve them in your work. I could see more amateurs helping the professionals in the data analysis or setting up and operating equipment. This is already happening in some areas, but it could happen more.

This year will bring another exciting event: Comet Siding Spring will fly by Mars, in a distance of only a bit over 100 000 km. Imagine a comet, possibly several km in size, flying by the Earth at less than 1/3 of the distance to the Moon! This will lead to a spectacular meteor storm on Mars. Spacecraft operators at ESA, NASA, and JAXA have started asking questions: How many dust particles will hit my spacecraft? They are fast, 56 km/s, and a particle of only 0.1 mm in size may cause damage. It turns out that the answer to this is not easy and cannot really be given. While predictions were made before on the timing of encounters of the Earth with cometary dust, the actual activity levels and size distribution have not been properly modeled yet. Thus, there is still a lot of work to do for the meteor community: We would need good measurements of the size distribution and flux outside the atmosphere of meteoroid streams, then these would need to be compared to the activity of the parent comet. Only after existing meteoroid streams have been compared with observations of their parents, we can really make good predictions.

So, go out and observe! Be it visual, with video, or collecting meteorites – in a time where the world is getting more and more aware that there is a real chance of being hit by a space object, with the fast information flow made possible via the internet, and the multiplication of the number of video surveillance cameras picking up

[1] European Space Agency and International Meteor Organisation.

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bright events, meteors and fireballs get more and more relevant and into the attention of the public and decision makers.

And if you want to relax after a long working day – there is nothing better than going out on a clear night and looking at the sky, waiting for a meteor to show up. This even works for professional meteor scientists! When I see the next meteor, I will wish for many more for all of us in the future.

References

Beatty K. (2014). "Small asteroid 2014 AA hits Earth". `http://www.skyandtelescope.com/news/Small-Asteroid-2014-AA-Hits-Earth-238481431.html` . (last accessed 2014 January 15).

Brown P. G., Assink J. D., Astiz L., Blaauw R., Boslough M. B., Borovička J., Brachet N., Brown D., Campbell-Brown M., Ceranna L., Cooke W., de Groot-Hedlin C., Drob D. P., Edwards W., Evers L. G., Garces M., Gill J., Hedlin M., Kingery A., Laske G., Le Pichon A., Mialle P., Moser D. E., Saffer A., Silber E., Smets P., Spalding R. E., Spurný P., Tagliaferri E., Uren D., Weryk R. J., Whitaker R., and Krzeminski Z. (2013). "A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors". *Nature*, **503**, 238–241.

Colas F., Zanda B., Vernazza P., Vaubaillon J., Bouley S., Gattacceccca J., Baratoux D., Birlan M., Cournede C., Fieni C., Hutzler A., Jambon A., Maquet L., Mousis O., Rochette P., Strajnic J., and Vachier F. (2012). "(FRIPON) Fireball Recovery and Interplanetary Matter Observation Network". *LPI Contributions*, **1667**, 6426.

Cooke W. J. and Moser D. E. (2012). "The status of the NASA All Sky Fireball Network". In *Proceedings of the International Meteor Conference, 30th IMC, Sibiu, Romania, 2011.* pages 9–12.

Jenniskens P., Shaddad M. H., Numan D., Elsir S., Kudoda A. M., Zolensky M. E., Le L., Robinson G. A., Friedrich J. M., Rumble D., Steele A., Chesley S. R., Fitzsimmons A., Duddy S., Hsieh H. H., Ramsay G., Brown P. G., Edwards W. N., Tagliaferri E., Boslough M. B., Spalding R. E., Dantowitz R., Kozubal M., Pravec P., Borovicka J., Charvat Z., Vaubaillon J., Kuiper J., Albers J., Bishop J. L., Mancinelli R. L., Sandford S. A., Milam S. N., Nuevo M., and Worden S. P. (2009). "The impact and recovery of asteroid 2008 TC_3". *Nature*, **458**, 485–488.

Johnson B. and Jenniskens P. M. (2014). "January and February Meteor Showers Detected by CAMS: the Cameras for Allsky Meteor Surveillance". In *American Astronomical Society Meeting Abstracts*, volume 223 of *American Astronomical Society Meeting Abstracts*. page #247.19.

Tancredi G., Ishitsuka J., Schultz P. H., Harris R. S., Brown P., Revelle D. O., Antier K., Le Pichon A., Rosales D., Vidal E., Varela M. E., Sánchez L., Benavente S., Bojorquez J., Cabezas D., and Dalmau A. (2009). "A meteorite crater on Earth formed on September 15, 2007: The Carancas hypervelocity impact". *Meteoritics and Planetary Science*, **44**, 1967–1984.

The IMO Support Fund

The IMO Council

Last year, we decided to change our policies with regard to the IMO Support Fund. We felt it was more productive to spend the annual budget available for this purpose no longer go to IMC support, but to amateur meteor research projects. To be eligible, these projects must

- be proposed by an IMO member;
- concern scientific and technological aspects of meteor observing;
- involve a medium- to long-term commitment of 3 years or more;
- return relevant results to the international community via the IMO;
- respect the conditions defined in a contract between the successful applicant and the IMO.

An application for a grant from the IMO Support Fund can be submitted at any time and must be addressed to the IMO President. It should include

- proper identification of the applicants, including their past realizations in meteor astronomy;
- a scientific and technological justification of the project;
- a timing to realize the project;
- references to support the competence of the applicants, and to support the feasibility of and the timing for the project proposed;
- a motivation why a grant from the IMO Support Fund is necessary to realize the project;
- a realistic budget of the costs and revenues involved, including the grant requested from the IMO Support Fund, financing by the applicants themselves or by the local, regional or national association to which they belong, and revenues from external sources;
- an explanation how the project will be managed during at least the first 3 years;
- a statement indicating whether you want to maintain your proposal for consideration during the next year should the budget for the current year be exhausted.

Successful applicants will be asked to sign a contract containing both the commitments of the applicants and additional requirements of the IMO that will constitute the terms under which the grant is provided. Under no circumstances will the IMO provide a blank check to the applicants! If the applicants do not live up to the terms specified in the contract, the IMO may withhold payment or even require a partial or full refund of the sums already paid. These terms will not only refer to the content of the project and the way it is managed, but also to a proper justification of the financial means provided, via invoices of the purchases agreed in the contract.

As the available budget is relatively small, the number of projects that can be financed will be limited to two or three per year. There are no deadlines; applications will be evaluated on the basis of first come, first served, and each proposal will be considered carefully on its merits. Proposals not meeting the criteria set above will be excluded from further consideration. In particular, proposed projects must be aimed at obtaining scientific results in a sustainable manner. Projects concerning outreach or education, or events of a more cultural nature will be considered out-of-scope.

Notice that the IMO Council reserves the right to support a cause at its own discretion when it feels it can further meteor astronomy in this way. The same holds for IMC support, which can still be made available in the form of waiving the standard registration fee, on a case-by-case basis. Requests for such support should be strongly motivated from a scientific perspective (required presence at a workshop, presentation of scientific results, participation in an international project, etc.). As emphasized above, grants of the IMO Support Fund will *not* be provided for outreach-oriented projects. This does not imply that the IMO fails to recognize the importance of outreach. For instance, the IMO Council recently appointed an IMO Outreach Officer in the person of Jure Atanackov. There are still many individuals who are serious about meteor astronomy, but who cannot afford IMO membership, for instance, but not exclusively, in developing countries. To encourage meteor astronomy, also in these countries, the IMO provides free membership with an electronic subscription to WGN to such individuals. Well-motivated requests for such gift memberships will be considered by the IMO Council.

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Conferences

Call for future IMCs: 2015 IMC

Paul Roggemans

The IMO invites candidate IMC organizers to present proposals to organize the IMC in 2015. To give interested parties full opportunity to prepare themselves it is important to plan future IMCs well in advance. IMO offers a guide to IMC organizers, the "IMC Essentials", which describes in detail all aspects of an IMC. Candidate IMC organizers should request and read these "IMC Essentials" in order to comply with the typical character of the IMC. Beyond the scenario for organizing an IMC, the IMC Essentials contain useful documents, templates and detailed statistics on past IMCs answering most questions future IMC organizers may encounter. Organizing an IMC involves a wide range of organizational and financial responsibilities. All these aspects are described in the "IMC Essentials" with complete examples of past IMC proposals and budgets.

Typically, an IMC is supposed to take place around the third week of September, from Thursday evening (arrival of the participants) to Sunday lunchtime (departure of the participants). Proposals are due 2014 May 1, and should be sent to Paul Roggemans, preferably in PDF-format or a Word document. Before you apply to become candidate IMC organizer make sure you can answer these preliminary questions:

1. **Who will organize the IMC?** Who is going to be the local organizer? Team work is essential for the local organizing committee and therefore you should indicate who will be part of a Local Organizing Committee. References to confirm your experience as conference organizer are indeed valuable.

2. **Why do you want to do it?** What is your motivation to organize an IMC? You may have particular reasons to organize an IMC and this may favour the selection of your proposal. As a non-profit event the IMC excludes commercial conference organizers not only for budgetary reasons, but also for the legal and fiscal regulations that prevent volunteers to work with or for any commercial partner.

3. **Where do you want to do it?** At what location do you want to organize an IMC? Why is this a good location? Can it easily be reached by plane, public transportation, and/or car? How many hours is it by public transport from the nearest major international airport? Provide a few pictures of the location, or, a web link to such pictures. Preferably, lectures and accommodation should be under the same roof, but there is no real objection to the lecture room being at a separate location within easy walking distance from the accommodation. Describe the accommodation at your disposal. Having a suitable and available accommodation to host an IMC is essential. The core business of an IMC are the lectures and posters which require a suitable lecture room. Do not propose any host without having a good quality lecture room.

4. **What will it cost?** With respect to the expenditures, take into account that the participants must be offered full board from Thursday evening, dinner, up to Sunday, lunch, inclusive. Of course, lecture room facilities should be accounted for, as well as a coffee break in the morning and in the afternoon. Finally, it is also customary to have a half-day excursion (max. 6 hours), usually on Saturday afternoon. Take into account that the price per participant should not exceed 170 EUR by much. Of this amount, 10 EUR must be reserved for producing and mailing the conference proceedings to the participants. Draft a preliminary budget for the IMC proposed. Mention all sources of income, in particularly sponsors or subsidies. As future prices for accommodation may not yet be available at the moment of your candidacy, work with current prices corrected for an estimate of inflation level and take into account exchange rate fluctuation against Euro if that is applicable.

   Note that, although the IMO provides the service of collecting the registration fees for you, the IMO will in principle *not* cover any negative balance that you might incur, so, please, draft your budget responsibly! A realistic budget for your proposed IMC is essential. Without a reliable financial plan an IMC proposal will be rejected with the request to provide a budget.

5. **Can it also be done in a later year?** We can only have one IMC every year. It is therefore important for us to know if you can also make this offer in a subsequent year. If there are reasons why the application cannot be postponed, please describe these reasons clearly!

We look forward to hear from candidate IMC organizers for 2015 or later conferences. The decision about the 2015 IMC will be taken no later than 30 June 2014 by the IMO Council confirmed by a memorandum of understanding to officialise the commitments.

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Meteor science

Some interesting meteor showers in EDMOND database

Jakub Koukal,[1] *Juraj Tóth,*[2,3] *Roman Piffl,*[1] *and Leonard Kornoš*[2]

This paper demonstrates the growing potential of EDMOND, a database of meteor orbital data, by presenting a summary analysis of eight meteor showers based on data collected over the period 2009 to 2012. The amount of input data (EDMOND 2.0 adds 79 402 new orbits) allows for improvement of mean orbits of Ursids, Andromedids, alpha Capriconids, Leonis Minorids, December Monocerotids, sigma Leonids, October Ursae Majorids and October Camelopardalids.

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1 Introduction

EDMOND (European viDeo MeteOr Network Database) is a database of meteor orbital data computed from meteors captured using video observation. It is the result of a broad international cooperation and sharing of data between EDMONd (European viDeo Meteor Observation Network) and the IMO VMN (International Meteor Organization Video Meteor Network). Contributors to EDMOND can be found in (Kornoš et al., 2014).

The EDMOND version 2.0 database (see web page `http://www.daa.fmph.uniba.sk/edmond`) consisted of 79 402 orbits in the period of 2009–2012 meeting specific minimum quality criteria. More details can be found in (Kornoš et al., 2013). With a substantial number of orbits based on relatively high quality meteor observations, detailed analysis of weak meteor streams and more precise characterization of well-known meteor showers is possible. This paper presents the analysis of eight meteor showers using data from the EDMOND 2.0 database as follows:

- Ursids and Andromedids (Irregular showers)
- α Capriconids (A regular shower which exhibits a higher population of bright meteors)
- Leonis Minorids and December Monocerotids (Regular showers with lower average brightness meteors)
- σ Leonids, October Ursae Majorids, and October Camelopardalids (Showers with lacking sufficient orbits in current database)

The calculated orbits for these showers are compared with mean orbits from the IAU MDC (IAU MDC, 2013). The mean shower orbits from the IAU MDC are listed in the Table 1. For completeness, possible parent bodies for these showers are listed in Table 2.

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2 Ursids (IAU 0015 URS)

The Ursid meteor shower is active between December 17 and December 25 with the maximum activity occurring around December 22 and ZHR $\sim$ 10. Returns of its parent body, comet 8P/Tuttle, are correlated to irregular shower maxima with ZHR $\sim$ 100 several years after the comet's perihelion passage.

The EDMOND database 2.0 contains 113 orbits of Ursids found by the *radiant–V_g* method used in UFO-ORBIT software (SonotaCo, 2009). A subset of 86 orbits was selected using the iterative method (Porubčan & Gavajdová, 1994; Arter & Williams, 1997) with $D_{SH} < 0.15$ (Southworth & Hawkins, 1963) for mean stream orbit characterization (Table 3, Figure 1). The average D_{SH} computed was $D_{SH} = 0.067 \pm 0.037$. The dataset contains only three hyperbolic orbits. The mean orbit from the EDMOND data is consistent within the standard deviation with the previously published orbit by (Jenniskens, 2006) obtained from a similar number of meteors.

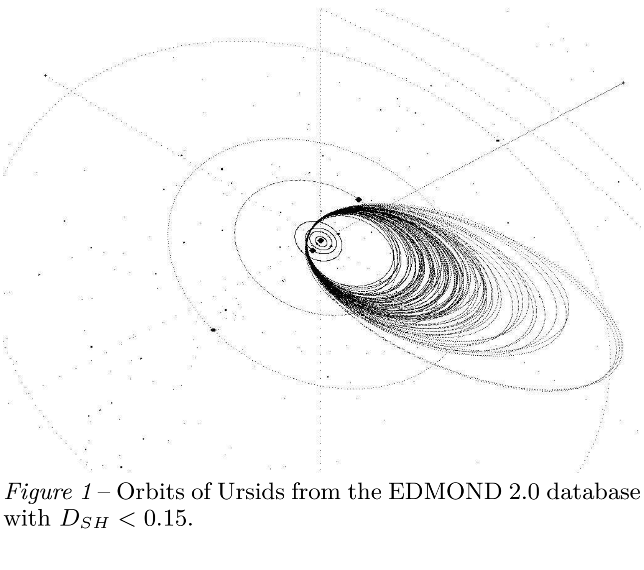

Figure 1 – Orbits of Ursids from the EDMOND 2.0 database with $D_{SH} < 0.15$.

3 Andromedids (IAU 0018 AND)

The Andromedids meteor shower is well known as a very active shower from the second half of the 19th century, when meteor storm displays produced ZHRs of 7000 in 1872 November 27 and 1885 November 27 (Jenniskens & Vaubaillon, 2007). A smaller meteor outburst with a ZHR $\sim$ 1000 was observed on 1892 November 24.

Table 1 – Orbital elements of the analyzed meteor showers according to IAU MDC (2013). For each shower the following parameters are provided: $\lambda_\odot$ – Solar longitude of shower maximum, RA, DEC – radiant position, dRA, dDEC – daily radiant motion, v_g – geocentric velocity (in km/s), a – semimajor axis (in AU), q – perihelion distance, ω – argument of perihelion, Ω – ascending node, i – inclination, N – number of orbits in the IAU MDC.

Name	ID	$\lambda_\odot$	RA	dRA	DEC	dDEC	v_g	a	q	ω	Ω	i	N
Ursids	15 URS	271°	219°.35	—	75°.34	—	33.0	4.62	0.944	204°.9	270°.74	51°.5	64
Andromedids	18 AND	232°	24°.2	+0°.63	32°.5	+0°.33	17.2	2.76	0.789	238°.9	231°.0	10°.0	18
α Capricornids	1 CAP	127°	306°.6	+0°.54	−8°.2	+0°.26	22.2	2.618	0.602	266°.67	128°.9	7°.68	36
Leonis Minorids	22 LMI	209°	159°.5	+1°.42	36°.7	−0°.36	61.9	286	0.616	102°.73	208°.36	125°.32	10
Dec. Monocerotids	19 MON	260°.9	101°.8	+0°.83	8°.1	−0°.05	42	50.7	0.193	128°.1	80°.2	35°.2	11
σ Leonids	136 SLE	27°.7	192°.6	—	3°.1	—	23	2.141	0.561	271°.9	8°.7	6°.2	—
Oct. Ursae Majorids	333 OCU	202°	144°.8	—	64°.5	—	54.1	5.9	0.979	163°.7	202°.1	99°.7	10
Oct. Camelopardalids	281 OCT	193°	166°	—	79°.1	—	46.6	368	0.993	170°.6	192°.57	78°.6	—

Table 2 – Possible parent bodies of analyzed meteor showers according to IAU MDC.

Shower name	Parent body
Ursids	8P/Tuttle
Andromedids	3D/Biela
α Capricornids	169P/Neat (= 2002 EX_{12})
Leonis Minorids	C/1739 K1 (Zanotti)
December Monocerotids	C/1917 F1 (Mellish)
σ Leonids	2002 GM_5 (?)
October Ursae Majorids	unknown
October Camelopardalids	unknown

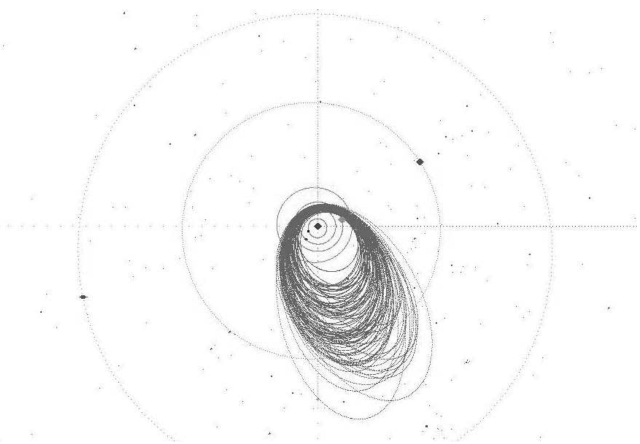

Figure 2 – Orbits of Andromedids from the EDMOND 2.0 database within $D_{SH} < 0.15$.

The meteor stream is associated with the parent comet 3D/Biela, which was observed with at least two nuclei in 1846 and 1852 after the break up in 1842/43. The last confirmed activity of the shower was observed on 1940 November 15 with a ZHR ∼ 30, while nowadays the shower has a low (less than ZHR = 1) and long lasted activity from the end of October till the end of November. The radiant of the stream members is not considerably concentrated and has a large diameter of about 20° and the geocentric velocity in the interval 17–19 km/s. 91 meteor orbits belonging to Andromedids were identified by the *radiant–V_g* method in the EDMOND 2.0 dataset (Figure 2). The most precise subset of 30 orbits (Figure 3) were selected for mean stream orbit characterization (Table 4) with an average $D_{SH} = 0.097 \pm 0.029$. The dispersion of mean orbits of previous authors is quite large. The mean orbit from the EDMOND data defined from 30 meteors is close to the published orbits by (Southworth & Hawkins, 1963; Jacchia, 1963; Jenniskens, 2006).

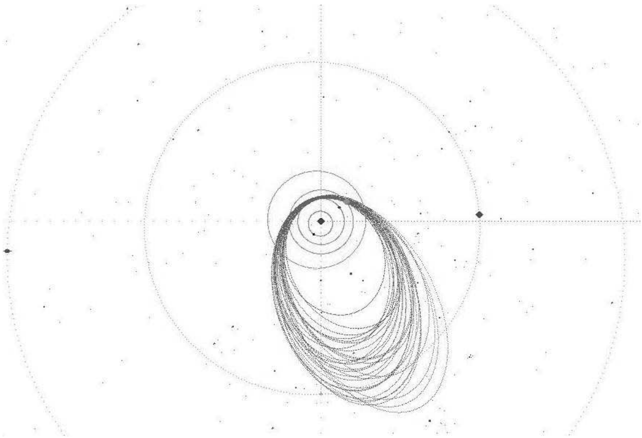

Figure 3 – Orbits of 30 Andromedids from the EDMOND 2.0 database with an average $D_{SH} = 0.097$.

4 α Capricornids (IAU 0001 CAP)

The α Capricornids shower is active approximately from July 15 to August 10 with no pronounced maximum activity. This aspect, together with the relatively high activity in this region on the sky (Aquarius–Capricornus) during this interval, makes it difficult to clearly distinguish the α Capricornids activity. The shower was discovered by the Hungarian duke M. Konkoly-Thege in 1871 and is known for a high rate of bright meteors, even fireballs (low population index) and broad maximum ZHR ∼ 5–10. The age of the stream is estimated to be in the range of 3500–5000 years (Jenniskens & Vaubaillon, 2010).

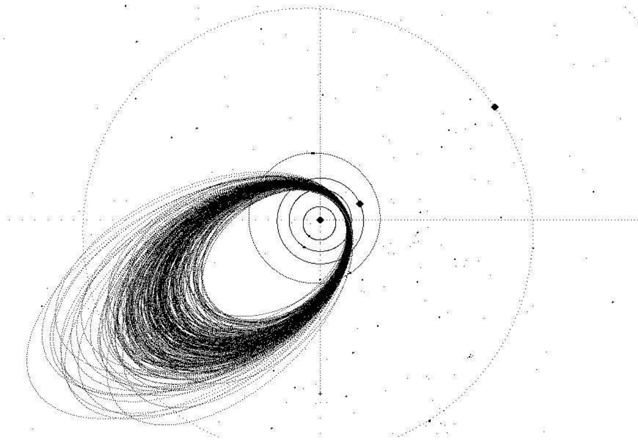

Figure 4 – Orbits of α Capricornids from the EDMOND 2.0 database within $D_{SH} < 0.15$.

Table 3 – Comparison of orbital elements of the mean Ursid orbit calculated from EDMOND 2.0 database compared to the Meteoroid Stream Working List (Jenniskens, 2006) and results by other authors. The following parameters are provided: q – perihelion distance, e – eccentricity, ω – argument of perihelion, Ω – ascending node, i – inclination, N – number of orbits, D_{SH} – orbital similarity criterion between EDMOND and results by other authors, RA, DEC – radiant position, v_g – geocentric velocity (km/s), H_1, H_2 – average beginning and terminal heights (km), respectively. σ is the standard deviation of the corresponding values.

	q	e	ω	Ω	i	N	D_{SH}	RA	DEC	v_g	H_1	H_2
EDMOND												
Mean	0.9368	0.800	206.°7	269.°7	52.°0	86		218.°8	76.°3	32.6	101.4	86.4
σ	0.0079	0.050	2.°3	1.°8	2.°0			5.°0	2.°1	1.1		
Other authors												
(Jenniskens, 2006)	0.944	0.796	205.°9	270.°74	51.°5	64	0.024	219.°35	75.°34	33.0		
(Kashcheyev & Lebedinets, 1963)	0.890	0.660	224.°0	270.°7	52.°0	—	0.268	190.°5	74.°7	32.0		

Table 4 – Orbital elements of the mean orbit of the Andromedids from EDMOND 2.0 database compared to other authors. The symbols used are the same as in Table 3.

	q	e	ω	Ω	i	N	D_{SH}	RA	DEC	v_g	H_1	H_2
EDMOND												
Mean	0.750	0.719	245.°2	224.°4	9.°4	30		22.°7	28.°6	18.1	92.4	84.8
σ	0.029	0.046	4.°0	4.°9	1.°8			4.°0	4.°3	1.4		
Other authors												
(Jenniskens, 2006)	0.789	0.714	238.°9	231.°0	10.°0	18	0.127	24.°2	32.°5	17.2		
(Jopek, 1992)	0.691	0.605	—	221.°0	12.°0	5	—	27.°2	34.°9	17.6		
(Porubčan & Gavajdová, 1994)	0.760	0.680	245.°2	207.°2	14.°3	3	0.153	3.°3	31.°8	18.1		
(Terentjeva, 1989)	0.738	0.698	248.°6	201.°9	12.°4	—	0.202	2.°6	26.°3	18.7		
(Terentjeva, 1989)	0.854	0.532	232.°4	234.°8	13.°8	—	0.302	17.°7	46.°3	14.1		
(Southworth & Hawkins, 1963)	0.777	0.732	242.°7	225.°5	7.°5	23	0.059	23.°7	9.°3	18.9		
(Jacchia, 1963)	0.740	0.726	247.°0	226.°0	6.°8	—	0.057	27.°7	25.°2	18.0		

Table 5 – Orbital elements of the mean orbit of α Capricornids from EDMOND 2.0 database compared to other authors. The symbols used are the same as in Table 3.

	q	e	ω	Ω	i	N	D_{SH}	RA	DEC	v_g	H_1	H_2
EDMOND												
Mean	0.592	0.760	268.°0	126.°9	7.°1	214		305.°9	−9.°5	22.3	93.5	83.5
σ	0.028	0.037	3.°4	3.°8	1.°5			3.°1	2.°2	1.2		
Other authors												
(Jenniskens, 2006)	0.602	0.770	266.°67	128.°9	7.°68	36	0.036	306.°6	−8.°2	22.2		
(Galligan & Baggaley, 2002)	0.550	0.745	273.°3	122.°3	7.°7	269	0.110	306.°7	−9.°3	23.4		
(Hasegawa, 2001)	0.594	0.766	267.°6	123.°8	7.°2	—	0.028	303.°4	−10.°6	22.2		
(Porubčan & Gavajdová, 1994)	0.626	0.726	266.°2	138.°5	4.°9	15	0.118	315.°9	−8.°7	20.6		
(Galligan, 2003)	0.544	0.733	275.°9	123.°5	7.°0	—	0.137	306.°4	−9.°9	22.5		
(Jopek & Froeschlé, 1997)	0.580	0.780	268.°0	134.°7	6.°0	—	0.062	314.°7	−8.°8	23.0		
(Sekanina, 1976)	0.620	0.677	267.°9	136.°6	6.°1	44	0.111	315.°9	−7.°1	19.7		
(Sekanina, 1973)	0.630	0.659	267.°2	147.°5	0.°9	28	0.206	327.°1	−11.°7	18.8		
(Lindblad, 1971)	0.592	0.765	267.°9	126.°1	7.°1	18	0.009	305.°4	−9.°6	25.0		
(Cook, 1973)	0.590	0.770	269.°0	127.°7	7.°0	21	0.021	308.°4	−9.°6	22.8		

The EDMOND 2.0 dataset consists of 345 orbits revealed by the *radiant–V_g* method (Figure 4). A subset of the 214 most precisely calculated orbits were selected for the mean stream orbit characterization (Table 5) with an average D_{SH} of 0.076 ± 0.035. The mean orbit from the EDMOND data defined from a large number of meteors is consistent with previously published orbits comparing by D_{SH} (Table 5).

5 Leonis Minorids (IAU 0022 LMI)

The Leonis Minorids is a weak shower that is active from October 19 to 27 with a maximum ZHR $\sim$ 2–5. At more than 61 km/s the geocentric velocity of its meteoroids is high and close to the parabolic limit.

The EDMOND 2.0 dataset contains 108 orbits. 32 of these orbits have an eccentricity larger than 1 (29.6%). A subset of 55 orbits (no hyperbolic solution) were selected for mean stream orbit characterization (Table 6, Figure 5) with an average D_{SH} of 0.080 ± 0.034. The mean well defined orbit based on 55 meteors from the EDMOND data is almost identical to previously published orbits.

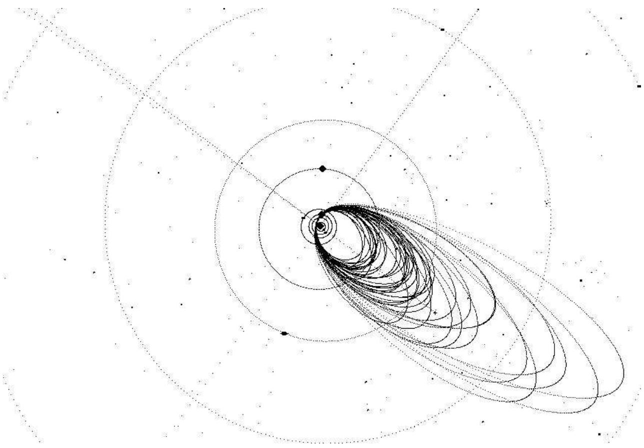

Figure 5 – Orbits of 55 Leonis Minorids from the EDMOND 2.0 database with an average $D_{SH} = 0.08$.

6 December Monocerotids (IAU 0019 MON)

The December Monocerotids meteor shower is active from November 9 to December 18 with a broad and low (ZHR $\sim$ 2–3) maximum around December 11. It was discovered by F. L. Whipple in 1954 after the analysis

Table 6 – Comparison of orbital elements of the Leonis Minorids mean orbit calculated from the EDMOND 2.0 database compared to the Meteoroid Stream Working List (Jenniskens, 2006) and results of other authors.

	q	e	ω	Ω	i	N	D_{SH}	RA	DEC	v_g	H_1	H_2
EDMOND												
Mean	0.617	0.953	102.°7	208.°2	124.°6	55		159.°1	37.°2	61.2	113.5	99.1
σ	0.023	0.050	3.°2	2.°6	1.°6			3.°0	1.°2	1.0		
Other authors												
(Jenniskens & Vaubaillon, 2010)	0.616	0.978	102.°73	208.°36	125.°32	10	0.028	159.°5	36.°7	61.9		
(de Lignie & Betlem, 1999)	0.641	0.980	106.°3	209.°9	124.°5	4	0.069	160.°7	37.°2	61.8		
(Cook, 1973)	0.650	0.988	106.°0	211.°7	124.°0	—	0.081	162.°7	36.°7	61.8		

Table 7 – Orbital elements of the mean orbit of the December Monocerotids from the EDMOND 2.0 database compared to other authors.

	q	e	ω	Ω	i	N	D_{SH}	RA	DEC	v_g	H_1	H_2
EDMOND												
Mean	0.188	0.983	129.°3	78.°6	35.°3	121		100.°7	8.°1	41.3	101.4	87.3
σ	0.017	0.021	2.°6	3.°0	2.°7			2.°3	1.°0	1.5		
Other authors												
(Jenniskens, 2006)	0.193	0.996	128.°1	80.°2	35.°2	11	0.038	101.°8	8.°1	42.0		
(Ohtsuka, 1989)	0.188	0.991	128.°9	80.°2	34.°9	15	0.026	102°	8.°3	41.6		
(Lindblad & Olson-Steel, 1990)	0.187	0.993	128.°9	81.°1	34.°9	12	0.037	102.°2	8.°3	41.8		
(Sekanina, 1976)	0.153	0.975	135.°8	72.°5	22.°3	30	0.282	95.°1	14.°5	40.0		
(Sekanina, 1973)	0.119	0.983	141.°2	68.°0	24.°7	52	0.356	92.°1	15°	41.6		
(Lindblad, 1971)	0.175	0.997	131.°0	82.°5	31.°5	—	0.097	100.°7	8°	42.0		
(Gartrell & Elford, 1975)	0.190	0.975	130.°0	82.°7	39.°9	3	0.100	106.°7	5.°9	40.5		
(Nilsson, 1964)	0.110	0.980	138.°9	76.°9	39.°0	6	0.204	102.°3	9.°5	42.2		
(Nilsson, 1964)	0.110	0.990	135.°3	73.°9	22.°6	4	0.275	95.°5	14.°5	41.3		
(Terentjeva, 1989)	0.121	0.965	141.°9	89.°0	22.°3	—	0.385	113.°7	13.°9	41.6		
(Nilsson, 1964)	0.200	0.990	131.°5	77.°3	18.°7	4	0.293	96.°8	15.°1	40.6		
(Jacchia, 1963)	0.140	0.997	135.°8	77.°6	24.°8	3	0.224	100.°5	14°	42.4		
(Whipple, 1957)	0.186	—	128.°2	81.°6	35.°2	2	—	103.°7	7.°9	42.4		

of 144 photographic orbits recorded in 1936–1951 by the Harvard College Observatory.

The EDMOND 2.0 datasets contains 155 orbits of which 121 of them were used for mean stream orbit characterization (Figure 6, Table 7). The average D_{SH} of 121 members relative to the mean orbit solution is 0.081 ± 0.034. However, there are 36 hyperbolic orbits among 155 orbits, which is 23.2%. The number of December Monocerotids in EDMOND is about by one order larger than previous published observations. The final orbit is derived only with a small standard deviation.

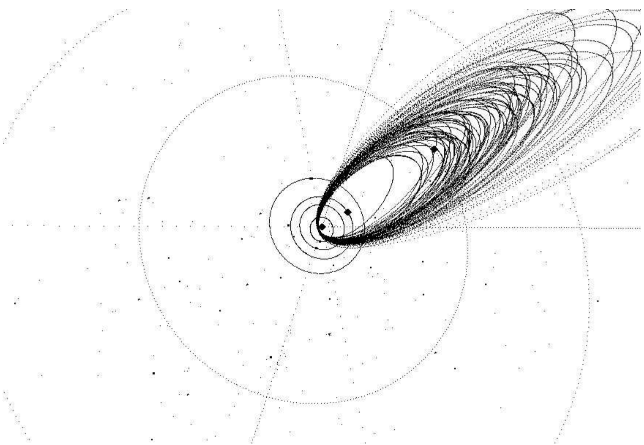

Figure 6 – Orbits of 121 December Monocerotids from the EDMOND 2.0 database with an average $D_{SH} = 0.081$.

7 σ Leonids (IAU 0136 SLE)

The σ Leonids is very weak shower with maximum ZHR $\sim$ 1–2 which is assumed to occur around April 18 (IAU MDC, 2013). The activity interval is not known and a similar situation occurs with the orbital description of the stream, where only a limited number of orbits is available, some of them based on visual observations.

The database EDMOND 2.0 contains 23 orbits and we selected 16 of them for mean stream orbit determination (Figure 7, Table 8). The average D_{SH} relative to the mean orbit of these 16 stream members is 0.083 ± 0.035. Our result defines a new mean orbit for the σ Leonids.

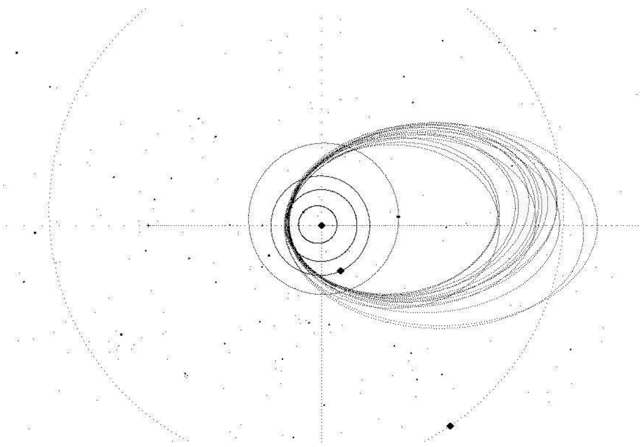

Figure 7 – Orbits of 16 σ Leonids from the EDMOND 2.0 database with an average $D_{SH} = 0.083$.

8 October Ursae Majorids (IAU 0333 OCU)

The October Ursae Majorids were discovered by (Uehara et al., 2006) based on 14 video orbits and confirmed by other authors and observational techniques (e.g. Gajdos, 2007). The database EDMOND 2.0 contains 107 orbits from this stream. 45 orbits were used for mean orbit of the stream characterization (Figure 8, Table 9). Their average D_{SH} relative to the mean so-

Table 8 – Orbital elements of the mean orbit of the σ Leonids from the EDMOND 2.0 database compared to other authors.

	q	e	ω	Ω	i	N	D_{SH}	RA	DEC	v_g	H_1	H_2
EDMOND												
Mean	0.685	0.728	255°.4	19°.3	5°.3	16		194°.5	3°.1	20.2	92.47	82.80
σ	0.032	0.030	4°.4	3°.3	1°.7			3°.4	1°.5	1.0		
Other authors												
(Porubčan & Gavajdová, 1994)	0.561	0.738	271°.9	9°.4	6°.2	—	0.300	193°.3	3°.1	23.0		
(Terentjeva, 1989)	0.605	0.734	266°.3	14°.5	2°.2	—	0.195	192°.6	−2°.3	21.2		
(Hoffmeister, 1948)	0.480	0.686	286°.0	13°.7	1°.9	vis	0.461	200°.7	−6°.3	—		

Table 9 – Orbital elements of the mean orbit of the October Ursae Majorids from the EDMOND 2.0 database compared to other authors.

	q	e	ω	Ω	i	N	D_{SH}	RA	DEC	v_g	H_1	H_2
EDMOND												
Mean	0.9739	0.868	162°.2	203°.0	100°.5	45		146°.7	63°.5	54.7	112.2	96.4
σ	0.0085	0.064	3°.4	1°.4	2°.4			3°.9	1°.5	1.1		
Other authors												
(Uehara et al., 2006)	0.979	0.875	163°.7	202°.1	99°.7	14	0.031	144°.8	64°.5	54.1		

lution is 0.088 ± 0.033, which represents a high internal orbital similarity among stream members similar to the above mentioned meteor streams. However, there are 20 orbits from 107 stream members with $e > 1$, which is 18.7%. It is natural to have some hyperbolic orbital solutions in the datasets, especially for streams with a relatively high geocentric velocity, where a small error in velocity measurements is transformed to a larger spread of orbital parameters, especially semimajor axis and eccentricity (Hajduková, 2008; Hajduková, 2011).

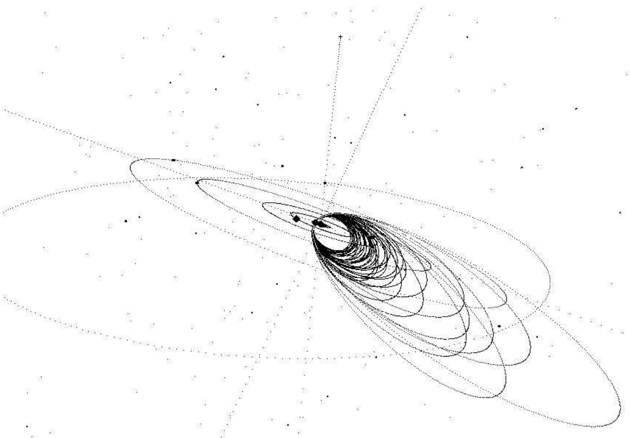

Figure 8 – Orbits of 45 October Ursae Majorids from the EDMOND 2.0 database with an average $D_{SH} = 0.088$.

9 October Camelopardalids (IAU 0281 OCT)

The October Camelopardalids is another recently identified meteor shower. Its identification is based on 13 orbits after the outburst in 2005 October 5 by (Jenniskens et al., 2005). The database EDMOND 2.0 contains 100 orbits. We used only 19 of them for characterization of the mean orbit of the stream (Figure 9, Table 10), where the mean value of D_{SH} is 0.080 ± 0.024. Our result differs from (Jenniskens et al., 2005) mainly in eccentricity. More detailed analysis is needed in the future.

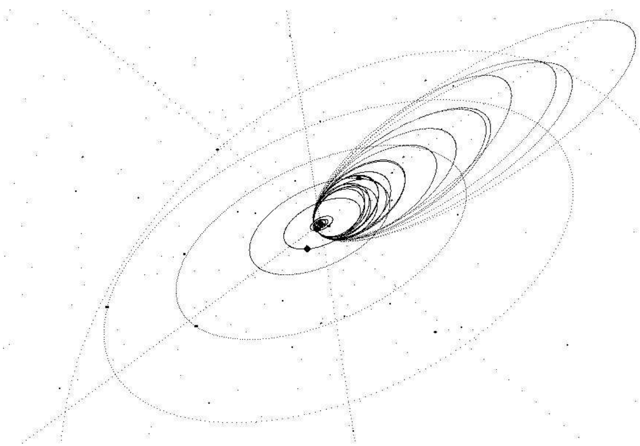

Figure 9 – Orbits of 19 October Camelopardalids from the EDMOND 2.0 database with an average $D_{SH} = 0.080$.

10 Conclusions

This paper demonstrates the benefits of data sharing. EDMOND has brought together many meteor observers and represents the combined data from 8 national networks. Availability of more data results in an improved accuracy and increased potential to identify statistically significant results.

To demonstrate the potential of the EDMOND database, we have analyzed datasets for eight meteor showers within the EDMOND 2.0 database (2009–2012) including established showers and showers from the IMO working list. In most cases we refined the mean orbits of these streams by using a larger number of available orbits from the EDMOND database, compared to previous works, with quite low dispersions in orbital parameters. We were able to improve the precision of all parameters in this way, compared with previous calculations.

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[1] `http://www.fireball.sk/edmond_map.html`

Table 10 – Orbital elements of the mean orbit of the October Camelopardalids from the EDMOND 2.0 database compared to other authors.

	q	e	ω	Ω	i	N	D_{SH}	RA	DEC	v_g	H_1	H_2
EDMOND												
Mean	0.9903	0.884	168°.6	192°.2	77°.8	19		164°.6	78°.5	45.3	106.0	93.2
σ	0.0044	0.067	2°.6	1°.1	1°.4			5°.6	1°.2	1.0		
Other authors												
(Jenniskens et al., 2005)	0.993	—	170°.5	192°.59	79°.3	13	—	164°.1	78°.9	47.3		
(Jenniskens et al., 2005)	0.993	0.997	170°.6	192°.57	78°.6	—	0.119	166°.0	79°.1	46.6		

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References

Arter T. P. and Williams I. P. (1997). "The mean orbit of the April Lyrids". *MNRAS*, **289**, 721–728.

Cook A. F. (1973). "A working list of meteor streams". In Hemenway C. L., Millman P. M., and Cook A. F., editors, *Evolutionary and Physical Properties of Meteoroids. Proc. IAU Colloq. 13.* NASA, pages 183–192.

de Lignie M. C. and Betlem H. (1999). "A double-station video look on the October meteor showers". *WGN*, **27:3-4**, 195–201.

Gajdoš Š. (2007). "Search for past signs of October Ursae Majorids". *Earth, Moon, and Planets*, **102**, 1–4.

Galligan D. P. (2003). "Radar meteoroid orbit stream searches using cluster analysis". *MNRAS*, **340**, 899–907.

Galligan D. P. and Baggaley W. J. (2002). "Wavelet enhancement for detecting shower structure in radar meteoroid data – II. application to the AMOR data set". In Green S. F., Williams I. P., McDonnell J. A., and McBride N., editors, *Dust in the Solar System and Other Planetary Systems.* Pergamon, New York, pages 48–60.

Gartrell G. and Elford W. G. (1975). "Southern hemisphere meteor stream determination". *Austr. J. Phys.*, **8**, 591–620.

Hajduková M. J. (2008). "Meteors in the IAU Meteor Data Center on hyperbolic orbits". *Earth, Moon, and Planets*, **102**, 67–71.

Hajduková M. J. (2011). "Interstellar meteoroids in the Japanese TV catalogue". *Publ. Astron. Soc. Japan*, **63**, 481–487.

Hasegawa I. (2001). "Parent objects of alpha Capricornid meteor stream". In Warmbein B., editor, *ESA SP 495.* ESA, pages 55–62.

Hoffmeister C. (1948). *Meteorstrome.* Leipzig: Barth, 286 pages.

IAU MDC (2013). "List of all meteor showers". `http://www.astro.amu.edu.pl/~jopek/MDC2007/Roje/roje_lista.php?corobic_roje=0&sort_roje=0` .

Jacchia L. G. (1963). "Meteors, meteorites, and comets: interrelations". In Middlehurst B. M. and Kuiper G. P., editors, *The Moon, Meteorites and Comets.* Chicago, IL: University of Chicago Press, pages 774–798.

Jenniskens P. (2006). *Meteor Showers and their parent comets.* Cambridge University Press. (pages 691-746).

Jenniskens P., Moilanen J., Lyytinen E., Yrjölä I., and Brower J. (2005). "The 2005 October 5 outburst of October Camelopardalids". *WGN*, **33:5**, 125–128.

Jenniskens P. and Vaubaillon J. (2007). "3D/Biela and the Andomedids: Fragmenting versus sublimating comets". *The Astronomical Journal*, **134**, 1037.

Jenniskens P. and Vaubaillon J. (2010). "Minor planet 2002 EX_{12} (=169P/Neat) and the alpha Capricornid shower". *The Astronomical Journal*, **139**, 1822.

Jopek T. (1992). "TV meteor stream searching". In Stohl J. and Williams I. P., editors, *Meteoroids and Their Parent Bodies*. Bratislava: Astron. Inst. Slovak Acad. Sci., pages 269–272.

Jopek T. and Froeschlé C. (1997). "A stream search among 502 TV meteor orbits. An objective approach". *Astron. Astrophys*, **320**, 631–641.

Kashcheyev B. L. and Lebedinets V. N. (1963). "Radar studies of meteors". *Smithsonian Contrib. Astrophys.*, **76**, 183–199.

Kornoš L., Koukal J., Piffl R., and Tóth J. (2013). "Database of meteoroid orbits from several European video networks". In Gyssens M. and Roggemans P., editors, *Proceedings of the International Meteor Conference, La Palma, Spain, Sep. 20-23, 2012*. International Meteor Organization, pages 21–25.

Kornoš L., Koukal J., Piffl R., and Tóth J. (2014). "EDMOND meteor database". In Gyssens M. and Roggemans P., editors, *Proceedings of the International Meteor Conference, Poznań, Poland, Aug. 22-25, 2013*. International Meteor Organization. (in press).

Lindblad B. A. (1971). "A computerized stream search among 2401 photographic meteor orbits". *Smithsonian Contrib. Astrophys.*, **12**, 14–24.

Lindblad B. A. and Olson-Steel D. (1990). "The Monocerotid meteor stream and comet Mellish". *Bull. Astron. Inst. Czechoslov.*, **41**, 193–200.

Nilsson C. (1964). "A southern hemisphere radio survey of meteor streams". *Austr. J.*, **17**, 205–256.

Ohtsuka K. (1989). "The December Monocerotids and P/Mellish". *WGN*, **17:3**, 93–96.

Porubčan V. and Gavajdová M. (1994). "A search for fireball streams among photographic meteors". *Planet. Space Sci.*, **42**, 151–155.

Sekanina Z. (1973). "Statistical model of meteor streams III. Stream search among 19303 radio meteors". *Icarus*, **18**, 253–284.

Sekanina Z. (1976). "Statistical model of meteor streams IV. A study of radio streams from the synoptic year". *Icarus*, **27**, 265–321.

SonotaCo (2009). "A meteor shower catalog based on video observations in 2007–2008". *WGN*, **37:2**, 55–62.

Southworth R. R. and Hawkins G. S. (1963). "Statistics of meteor streams". *Smithson. Contrib. Astrophys.*, **7**, 261–286.

Terentjeva A. K. (1989). "Fireball streams". In Lagerkvist C. I., Rickman H., and Lindblad B. A., editors, *Proceedings of the Asteroids, Comets and Meteors III, Uppsala University, June 12–16, 1989*. Uppsala: Universitet, pages 579–584.

Uehara S., SonotaCo, Fujiwara Y., Furukawa T., Inoue H., Kageyama K., Maeda K., Muroishi H., Okamoto S., Masuzawa T., Sekiguchi T., Shimizu M., and Yamakawa H. (2006). "Detection of October Ursa Majorids in 2006". *WGN*, **34:6**, 157–162.

Whipple F. (1957). "Some problems of meteor astronomy". In van de Hulst H. C., editor, *Radio Astronomy. Proc. IAU Symp. No. 4*. Cambridge: Cambridge University Press, pages 375–389.

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A meteor cluster detection algorithm

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We present an algorithm to identify groups of meteors within all-sky meteor network observations that are clustered in radiant, velocity, and time. These meteor clusters may reveal new minor meteor showers or uncover false negatives for known shower association. Sporadic meteoroid sources and established meteor showers exhibiting spatiotemporal proximity to identified clusters are reported by the algorithm for end-user reference, as well as the orbital similarity of cluster members quantified using the Drummond D-criterion. This algorithm will be integrated into the existing data-processing pipeline at the NASA Meteoroid Environments Office to alert staff in near-real time of clustered meteor events.

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1 Introduction

The NASA Meteoroid Environments Office (MEO) models and measures meteoroid environments with a focus on spacecraft operations and risk mitigation. While the bulk of the risk to spacecraft comes from the ever-present sporadic meteoroid background (McBride, 1997), major meteor showers do create times of elevated threat. Consequently, one of the MEO's goals is to identify, measure, and forecast meteor shower activity. This requires being able to accurately identify and catalog apparent meteor showers, especially those in outburst. The ability to identify regions of localized meteoroid activity is a preliminary step to finding new meteor showers. Identifying shower meteors is also a prerequisite to isolating the sporadic meteoroid environment. An aggressive shower meteor identification algorithm like the one presented here is therefore desirable if one wishes to study the sporadic meteoroid environment free of shower meteor contamination.

We apply our algorithm to data from two all-sky meteor networks: the NASA All-Sky Fireball Network and the Southern Ontario All-Sky Meteor Network (SOMN) operated by the University of Western Ontario (UWO). NASA's Fireball Network currently contains eight ground-based optical cameras, six of which lie in the southeastern United States and two which lie in the Southwest; details about the network can be found in Cooke & Moser (2012). UWO's SOMN network has 10 similar cameras placed in southwestern Ontario (Brown et al., 2010a). These networks are among an array of all-sky systems currently surveying meteoroid orbits, accompanied by the NASA-funded Cameras for All-sky Meteor Surveillance (CAMS) network (Jenniskens et al., 2011) and others.

Data from both of these camera networks are processed by the All Sky and Guided Automatic Realtime Detection (ASGARD) software developed by Robert J. Weryk (Weryk et al., 2008; Brown et al., 2010a). ASGARD autonomously correlates simultaneous meteor events in adjacent cameras and calculates trajectories and orbits. At the time of writing there have been over 14 000 meteor events observed between these two networks, dating back to 2006. While 14 000 pales in comparison to the millions of meteors detectable by radar systems (Brown et al., 2010b), these optical all-sky networks detect only the brightest meteors: those of magnitude -3 or brighter (Brown et al., 2010a).

Meteors are checked for association with known showers, but there is currently no system in place to alert our staff of possible new showers. Meteors not assigned to a known shower are by default classified as part of the sporadic background, although instrumental uncertainties produce a certain number of false negatives for shower association. The identification of clustered events assists in quantifying those false negatives as well as potentially identifying new minor meteoroid streams. In practice, this algorithm establishes a third category of meteor observations – those that do not fulfill the criteria for membership in a known shower, but still exhibit an anomalous degree of clustering.

Section 2 describes the cluster detection criteria and the algorithm output. Section 3 presents a simulated set of random meteor radiants and describes the results of our algorithm's application to both the real and simulated data sets.

2 Methods

To identify meteor clusters, the algorithm searches for sets of meteors with low radiant and velocity dispersions. This method indirectly requires the meteoroids to share similar orbits, as the velocity and radiant constrain the orbit in space. This is a computationally efficient and transparent approach to identifying meteor clusters, as it reduces the degrees of freedom necessary to specify an elliptical orbit from five (e.g. q, e, i, ω,and Ω) to three (e.g. α, δ, and v). While we do not use orbital elements to determine cluster membership, we do report D-parameters for identified clusters for user reference.

More sophisticated approaches to stream identification exist in the literature; for instance, the 3D wavelet transform technique of Brown et al. (2010b) has been applied to three million meteoroid orbits obtained using the MEO-sponsored Canadian Meteor Orbit Radar (CMOR). This technique works well for large-number

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statistics. Note that the observed meteoroid size distribution is approximated by $dN(m) \propto m^{-s}dm$ where $s \approx 2.34$ (Wiegert et al., 2009). While CMOR detects particles with a mean mass near 10^{-7} kg (Brown et al., 2010b), 90% of SOMN meteors had pre-atmospheric masses between 10^{-4} and 10^{-2} kg (Brown et al., 2010a). This results in an observed meteor flux that is orders of magnitude lower; an alternative approach must therefore be sought for optical all-sky networks which simply do not provide the required abundance of data.

2.1 Cluster identification criteria

Our cluster identification criteria mimic the shower association criteria currently implemented in the ASGARD meteor detection software. ASGARD associates meteors with a known shower when the meteor radiant lies within 7.5° of the shower radiant, the meteor velocity lies within 20% of the shower velocity, and the meteor occurs while the shower in question is active. Unlike catalogued showers, our clusters lack an established radiant, velocity, and duration. Thus, we instead search the data for clusters of five or more meteors that satisfy the following:

1. All meteors occur during a three-night interval.
2. All meteors lie no more than 7.5° from a common mean radiant.
3. The minimum and maximum velocities lie within 20% of an intermediate value (i.e., $0.8 * v_{max} \leq 1.2 * v_{min}$).

The above criteria allow us to identify clusters without having prior knowledge of the mean stream radiant or velocity. Once clusters have been identified, we organize them into groups of overlapping clusters – clusters linked in chains by shared members.

2.2 Algorithm output

Our algorithm reports clusters, their constituent meteors, and their demonstrated groupings. For user reference, we also identify and report meteor showers and sporadic sources that lie near the clusters in space and time. Spatially, we take "near" to mean within 15° of the cluster center. We take temporally "near" to mean that there is overlap between the three-day cluster interval and the period of shower activity. If the period is unknown, we set it to ±3° solar longitude. In contrast, ASGARD currently ignores (i.e., never reports) showers that do not provide a period of shower activity, as explained by R.J. Weryk (personal communication, Jun. 26, 2013). Sporadic sources included in the output are the Antihelion, North and South Apex, and North Toroidal sources. We exclude sources that lie in the southern hemisphere or occur during daylight. Meteor shower data is drawn from the same catalog used by ASGARD. Sporadic source data is drawn from Campbell-Brown (2008) who identified sporadic sources using radar meteor orbits obtained with CMOR.

We also report the orbital similarity parameter D proposed in Drummond (1981) – a modification of the original D-parameter discussed in Southworth & Hawkins (1963) – as a measure of orbital similarity between each cluster meteor and the mean cluster orbit. Each of the four terms in D is weighted such that it falls between 0 and 1:

$$D^2 = \left(\frac{e_2 - e_1}{e_2 + e_1}\right)^2 + \left(\frac{q_2 - q_1}{q_2 + q_1}\right)^2 + \left(\frac{I_{21}}{180°}\right)^2 + \left(\frac{e_2 + e_1}{2}\right)^2 \left(\frac{\theta_{21}}{180°}\right)^2, \quad (1)$$

where I_{21} is the angle between the orbital planes, and θ_{21} is the angle between the perihelion points on each orbit. I_{21} and θ_{21} are defined in terms of orbital elements:

$$I_{21} = \arccos[\cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Omega_2 - \Omega_1)], \quad (2)$$

$$\theta_{21} = \arccos[\sin \beta_1 \sin \beta_2 + \cos \beta_1 \cos \beta_2 \cos(\lambda_2 - \lambda_1)], \quad (3)$$

$$\lambda = \arctan(\cos i \tan \omega) + \Omega, \quad (4)$$

$$\beta = \arcsin(\sin i \sin \omega), \quad (5)$$

where λ and β are the ecliptic longitude and latitude of perihelion, and $\lambda = \lambda + 180°$ if $\cos \omega < 0$. This formulation of the Drummond D-parameter is presented in Galligan (2001) as D_D. We simplify the computation of the mean orbit by using the mean of each orbital element; the shortcomings of this approach are described in Voloshchuk (1999). The D-parameter of each cluster member relative to the cluster mean is provided in the algorithm output. We also report the D-parameter thresholds for meteoroid stream association taken from Galligan (2001). Threshold values are applied to our data and discussed further in Section 3. We reiterate that the D-parameter is not currently implemented as a cluster membership criterion.

3 Results

In this section we discuss the results of applying our meteor cluster detection algorithm to two data sets. The first data set consists of simulated random meteor radiants; we use this data set to quantify the frequency with which clusters occur at random. The second data set is the entire set of meteors detected by the NASA Fireball and SOMN all-sky networks.

3.1 Simulated meteor data

The typical separation between meteors in our simulated data will be inversely proportional to the number of meteors simulated. Therefore, we use the rate of meteor detection by the Fireball and SOMN networks as an input to our simulated data.

We first obtain a probability distribution for the number of meteors per night from the number of non-shower meteor observations made by the two networks (Figure 1). We pull from this distribution to determine the number of meteors each night in our simulated data set, which spans the same time period as the observations.

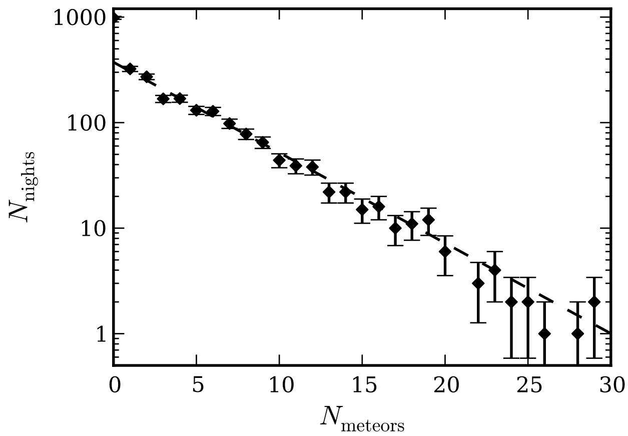

Figure 1 – Number of nights with N_{meteors} non-shower meteors, with $\sqrt{N}$ error bars, over the entire span of meteor observations made with both the Fireball and SOMN networks. We have fit the data with a simple logarithm (dashed line) and used this fit to select the number of meteors per night in our simulated data set.

We also mimic the dependence of meteor frequency on time of night that occurs in the data (Figure 2). Meteors increase in number over the course of the night as the Earth rotates the observer towards the direction of orbital motion. We approximate the observed trend with a quadratic fit to the data.

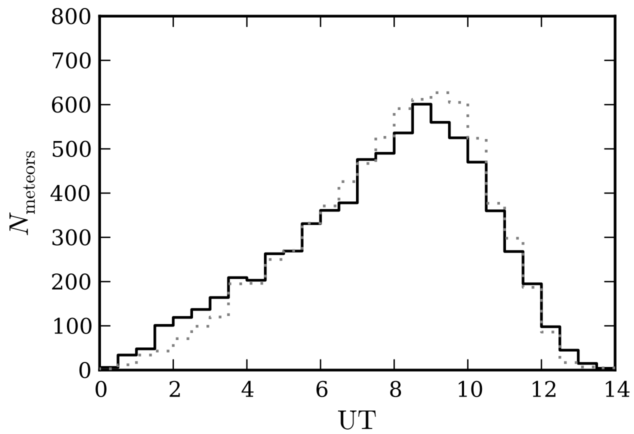

Figure 2 – Number of non-shower meteors per hour detected by the Fireball and SOMN networks (solid black line) and simulated by the authors (dotted gray line). The meteor rate increases over the course of the night as the cameras rotate with the Earth's surface to face the direction of the Earth's orbital motion. The decrease in number of meteors per hour from 8:30 UT to 14:00 UT stems from the decreasing fraction of days during which it is dark during those hours. In order to generate times for our simulated data, we generated a time-of-night probability distribution function from a quadratic fit to the number of observations occurring during hours that are always nighttime hours. We define "at night" to be between nautical dusk and dawn.

For each of n simulated meteors that we produce on a given night, we select a time between nautical dusk and dawn using the time-of-night probability distribution in Figure 2. We also select random isotropic altitude and azimuth coordinates for the meteor radiant, which we convert to right ascension and declination using the observer location, date, and time.

We have chosen not to incorporate some of the complexities of the all-sky networks. For instance, we do not reproduce the increase in the number of meteor detections over the past seven years as the networks added cameras, nor do we simulate the variation of meteor flux with time of year (McKinley, 1961). We do not simulate periods of bad weather. All of these effects can alter the spatial distribution and density of meteor radiants, but we expect these secondary effects to be insignificant compared to the difference seen between our real and simulated data. We also do not attempt to compute meteor velocities and thus we compare the number of meteor clusters in our simulated data to those in observations prior to applying the velocity criterion.

3.2 Meteor network data

In this section, we present results from the entire existing database. Meteors that had already been assigned to a known shower were excluded from this analysis. Meteors with a convergence angle (Q) less than 15 degrees were also excluded. The convergence angle refers to the angle between the meteor trajectory and the line or plane determined by the locations of cameras used in the observation (Jenniskens et al., 2000, p. 279).

We began with a raw data set of 14 178 meteors (as of Aug. 2, 2013). Application of the non-association and convergence angle criteria reduced the number of meteors to 7 612. These meteors were first searched for clusters based on the radiant criterion alone; this resulted in 3 105 unique clusters within 572 unique cluster groups. These clusters were then examined for fulfillment of the velocity criterion; this reduced the number of unique clusters to 2 592 and the number of unique groups to 552.

These numbers are in stark contrast to the simulated data results (Table 1). In general, many more clusters were detected in the all-sky data than in our simulated data. We generated 100 realizations of simulated meteor data in order to characterize the rate of occurrence of meteor clusters and meteor cluster groups. We find that, on average, about 70 meteor clusters occur by chance (± 14; see Table 1); over 3000 spatial clusters occurred in the data, which is a difference of about 200σ. More cluster overlap occurs in observations than in our random simulated meteors, as one would expect for clusters stemming from streams, false negatives for stream membership, and sporadic sources. The number of observed groups of clusters in the real data also greatly exceeds the number of cluster groups occurring

Table 1 – Comparison of real and simulated data results. Meteors were processed by the radiant clustering portion of the algorithm only, resulting in N_{clusters} unique clusters contained within N_{groups} unique cluster groups. The velocity clustering portion of the algorithm was not used since we did not simulate velocities in the simulated data set.

Data type	N_{clusters}	N_{groups}
Real	3 105	572
Simulated	70 ± 14	53 ± 10

randomly. While our simulations produced 53±10 cluster groups, the data produced 572. The observations exhibit a much greater degree of clustering than would occur by chance.

We then explored the orbital similarity parameters and threshold values introduced in Section 2. These thresholds are inclination dependent, separated into low-prograde ($i < 10°$), high-prograde ($10° \leq i < 90°$), and retrograde orbital regimes (Galligan, 2001). For each inclination regime, Galligan provides thresholds for recovering 50%, 70%, and 90% of meteoroid stream members. The results of applying these thresholds, along with the results previously discussed, are all contained in Table 2. The thresholds currently being applied in the actual algorithm output are for 70% stream recovery; 902 of the 2 592 meteor clusters retained at least five members after applying the thresholds, and similarly 96 of the 552 cluster groups retained all their constituent clusters. The 50% and 90% thresholds provide additional means of applying more stringent or more lenient filters for orbital similarity.

Table 2 – Meteor, cluster, and cluster group counts at various stages of data-processing. Each step is given in chronological order, beginning with initializing the database. We then omit meteors already assigned to showers, followed by meteors with low convergence angles. Clusters are initially constructed by radiant alone; they are then reduced to those also satisfying the velocity criterion. Finally, we provide statistics for application of the three sets of D-parameter thresholds.

Step	$N_{meteors}$	$N_{clusters}$	N_{groups}
Initialize	14 178	—	—
Not Shower	9 156	—	—
$Q > 15$	7 612	—	—
Radiant	3 020	3 105	572
Velocity	2 780	2 592	552
90%	2 279	1 656	240
70%	1 788	902	96
50%	1 234	378	28

Many clusters were flagged for their proximity to known shower radiants, as anticipated; 1 456 of the 2 592 final clusters were within 15° of a known shower radiant. We observed an abundance of possible false negatives for shower members in the data, especially near the Perseid and Geminid meteor shower radiants, the largest producers of meteor events in our database. A visual representation of this phenomenon can be found in Figure 3, where a symmetrical distribution of tightly-grouped clusters is evident around the Perseid shower radiant. This behavior is a natural consequence of observational uncertainties.

The algorithm also blindly identified a clustering event that had already been manually identified by MEO staff (Figure 4). This cluster was identified following the large lunar impact on March 17, 2013 (Suggs et al., 2013), when MEO staff probed the Fireball database in search of any corresponding anomalies. The three minor Virginid showers in Figure 4 do not have solar longitude ranges provided in the shower catalog, and were therefore never associated with these cluster meteors. Detection of this event validates the algorithm's ability to identify new or missing showers.

4 Conclusions

Our algorithm found many meteor clusters in all-sky observations and very few in simulated random meteor radiants, indicating that it identifies meteor clusters with low "noise". It successfully and blindly identified a cluster of interest known to be present in the database. While many clusters were found to lie near known sources, the algorithm also found 541 clusters not in proximity to any known showers or sporadic meteoroid sources – clusters which may warrant further study.

The algorithm also illustrated the prevalence of false negatives being rejected by the shower association pipeline. The algorithm's inclusion in the existing data-processing pipeline will allow the MEO to take a more aggressive approach to shower meteor identification, removing unidentified showers and groups of false negatives – an important step toward studying the sporadic meteoroid environment in isolation. However, as sporadic meteors are shower meteors that have undergone significant dynamical evolution (Wiegert et al., 2009), we do expect them to also exhibit an inherent degree of clustering. The potential to falsely identify these sporadic meteors as possibly belonging to new or existing meteor showers is inherent to any aggressive cluster identification approach.

The D values may be employed in the future as an additional criterion to more stringently require orbital similarity among cluster members, or another D-parameter may be used altogether. Further study of prominent clusters may ultimately lead to identification of new minor meteor showers as well, especially if such clusters are found to occur annually.

The algorithm has completed initial testing and is now operational, sending reports directly to MEO staff when clusters appear in the data.

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References

Brown P., Weryk R. J., Kohut S., Edwards W. N., and Krzeminski Z. (2010a). "Development of an All-Sky Video Meteor Network in Southern Ontario, Canada The ASGARD System". *WGN, Journal of the IMO*, **38:1**, 25–30.

Brown P., Wong D. K., Weryk R. J., and Wiegert P. (2010b). "A meteoroid stream survey using the Canadian Meteor Orbit Radar. II: Identification of minor showers using a 3D wavelet transform". *Icarus*, **207**, 66–81.

Campbell-Brown M. (2008). "High resolution radiant distribution and orbits of sporadic radar meteoroids". *Icarus*, **196:1**, 144–163.

Cooke W. J. and Moser D. E. (2012). "The status of the NASA All Sky Fireball Network". In Gyssens M. and Roggemans P., editors, *Proceedings of the International Meteor Conference, 30th IMC, Sibiu, Romania, 2011*. International Meteor Organization, pages 9–12.

Drummond J. D. (1981). "Earth-orbit-approaching comets and their theoretical meteor radiants". *Icarus*, **47**, 500–517.

Galligan D. P. (2001). "Performance of the D-criteria in recovery of meteoroid stream orbits in a radar data set". *MNRAS*, **327**, 623–628.

Jenniskens P., Gural P. S., Dynneson L., Grigsby B. J., Newman K. E., Borden M., Koop M., and Holman D. (2011). "CAMS: Cameras for Allsky Meteor Surveillance to establish minor meteor showers". *Icarus*, **216**, 40–61.

Jenniskens P., Rietmeijer F., Brosch N., and Fonda M., editors (2000). *Leonid Storm Research*. Earth, Moon and planets. Kluwer Academic Publishers.

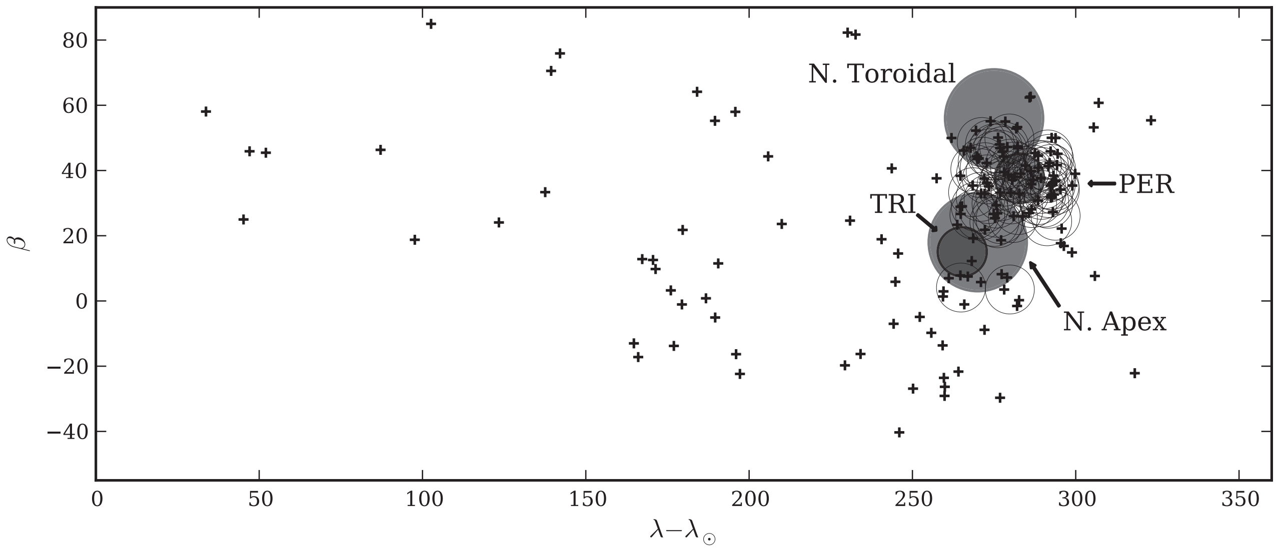

Figure 3 – A large collection of meteors (solar longitudes 140°–143°) symmetrically distributed about and obscuring the active Perseids (PER) radiant. The '+' markers denote all the non-shower meteors. The thin circles enclose unique groups of five or more meteors identified as clusters. The active August Triangulid (TRI) radiant and the two nearby sporadic sources are also shown. Two cluster groups were identified; the large cluster group centered about the Perseid radiant contains many strong candidates for false-shower-negatives.

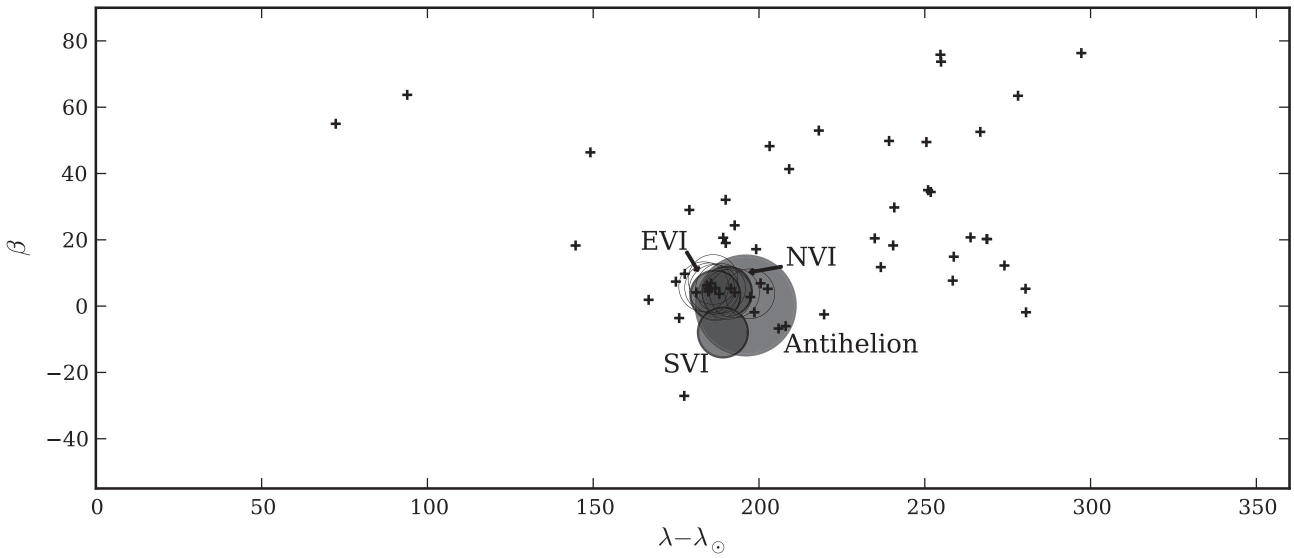

Figure 4 – A group of clusters from the middle of March (solar longitudes 354°–357°). The '+' markers denote all the non-shower meteors. The thin circles enclose unique groups of five or more meteors identified as clusters. The active Northern March Virginid (NVI), eta Virginid (EVI), and Southern March Virginid (SVI) radiants are shown, as well as the Antihelion source. A single cluster group was identified. This grouping of meteors had been manually identified before applying the algorithm to our data.

McBride N. (1997). "The importance of the annual meteoroid streams to spacecraft and their detectors". *Advances in Space Research*, **20**, 1513–1516.

McKinley D. W. R. (1961). *Meteor science and engineering.* New York, McGraw-Hill, 1961.

Southworth R. B. and Hawkins G. S. (1963). "Statistics of meteor streams". *Smithsonian Contributions to Astrophysics*, **7**, 261–285.

Suggs R., Cooke W., Kingery A., Kring D., Moser D., and Suggs R. (2013). "Large Meteoroid Impact on Moon on 17 March 2013". In *Lunar Science Virtual Forum.* NASA Ames Research Center.

Voloshchuk Y. (1999). "Mean orbits of meteor streams". In Baggaley W. J. and Porubcan V., editors, *Meteoroids 1998.* pages 199–202.

Weryk R. J., Brown P. G., Domokos A., Edwards W. N., Krzeminski Z., Nudds S. H., and Welch D. L. (2008). "The Southern Ontario All-sky Meteor Camera Network". *Earth, Moon and Planets*, **102**, 241–246.

Wiegert P., Vaubaillon J., and Campbell-Brown M. (2009). "A dynamical model of the sporadic meteoroid complex". *Icarus*, **201**, 295–310.

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Table 3 – Example output of cluster algorithm for three degrees of solar longitude ($16° \leq \lambda_\odot \leq 19°$). Columns include right ascension, declination, meteor velocity, solar longitude, ecliptic latitude, sun-centered ecliptic longitude, and the orbital similarity parameter D, from left to right. Two cluster groups are present, with the first containing a single cluster (1a), and the second containing two (2a, 2b). Below the horizontal lines are the mean values for that cluster. Reported below the clusters are the nearby sources: the Lambda Virginids (LVI), and the Antihelion source, with their respective values taken from ASGARD's shower catalog and Campbell-Brown (2008). All cluster members in this output had an inclination i less than 10°, so according to Table 1 of Galligan (2001) the threshold D values for 50%, 70%, and 90% stream recovery are 0.04, 0.06, and 0.09, respectively. Note that none of the above clusters would remain if any of these sets of thresholds were applied as a criterion for cluster membership, as they would not retain the minimum five members.

Cluster	α (°)	δ (°)	v (km/s)	$\lambda_\odot$ (°)	β (°)	$\lambda - \lambda_\odot$ (°)	D
1a	217.3	−15.88	39.5	16.59	−1.1	203.48	0.42
	211.26	−18.39	30.9	17.573	−5.37	197.86	0.04
	213.19	−8.77	34.3	18.113	4.32	195.85	0.09
	205.59	−14.77	30.9	18.864	−3.89	190.2	0.16
	205.45	−19.37	30.8	18.94	−8.22	191.66	0.14
	210.56	−15.44	33.3	18.016	−2.85	195.81	
2a	185.1	0.35	20.5	16.591	2.35	167.95	0.09
	193.15	−6.88	22.8	16.751	−1.15	178.02	0.06
	194.16	4.83	24.7	16.894	10.03	174.24	0.13
	188.39	4.56	23.4	16.966	7.52	168.93	0.12
	190.63	−6.31	22.6	18.913	−1.6	173.34	0.05
	190.29	−0.69	22.8	17.223	3.43	172.5	
2b	182.45	−2.96	18.2	16.357	−1.74	167.07	0.14
	185.1	0.35	20.5	16.591	2.35	167.95	0.09
	193.15	−6.88	22.8	16.751	−1.15	178.02	0.06
	188.39	4.56	23.4	16.966	7.52	168.93	0.12
	190.16	−8.15	22.3	17.623	−3.47	174.91	0.04
	190.63	−6.31	22.6	18.913	−1.6	173.34	0.05
	188.31	−3.23	21.6	17.2	0.32	171.7	
LVI	210.7	−10.2	26.8	20.0	—	—	
Antihelion	—	—	—	—	0.2	196.0	

Preliminary results

Results of the IMO Video Meteor Network — October 2013

Sirko Molau,[1] *Javor Kac,*[2] *Stefano Crivello,*[3] *Enrico Stomeo,*[4] *Geert Barentsen,*[5] *and Rui Goncalves*[6]

The IMO Video Meteor Network preliminary results are presented for October 2013, based on data obtained by 75 cameras of the Network. The flux density profile of the Orionids is presented. The algorithm for population index is improved. Population index values for four nights around the maximum are estimated.

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1 Introduction

The weather in October was mixed: observers in northern and eastern Europe enjoyed very good observing conditions, but observers in Italy and Spain were less fortunate. Nonetheless, 49 out of the overall 75 active cameras achieved at least twenty observing nights. This large number cannot disguise the fact that there were many partly cloudy nights, and in particular in southern Europe there was hardly any night with fully clear skies. The effective observing time summed up to over 9 300 hours, almost 600 hours more than in the previous year (Molau et al., 2013a). However, the meteor count remained at about 43 000, i.e. we recorded just a few hundred meteors more than in 2012 (Table 1 and Figure 1).

In October, Maciej Maciejewski reconstructed his cameras. Pav35 and Pav36 got new Mintron cameras and Computar $f/0.8$, 3.8-mm lenses, which was quite conducive for their detection rate. One of the old cameras was recycled, so that now Maciej is operating a fourth camera Pav60. Also Jörg Strunk equipped some of his Mincams with new Mintron cameras. Furthermore, since the sky has four compass points, Sirko Molau installed a fourth Mintron camera Remo4 with $f/0.8$, 8-mm Computar lens on the roof of his house in Ketzür (Figure 2). The camera achieves a stellar limiting magnitude of +6.5 during clear nights.

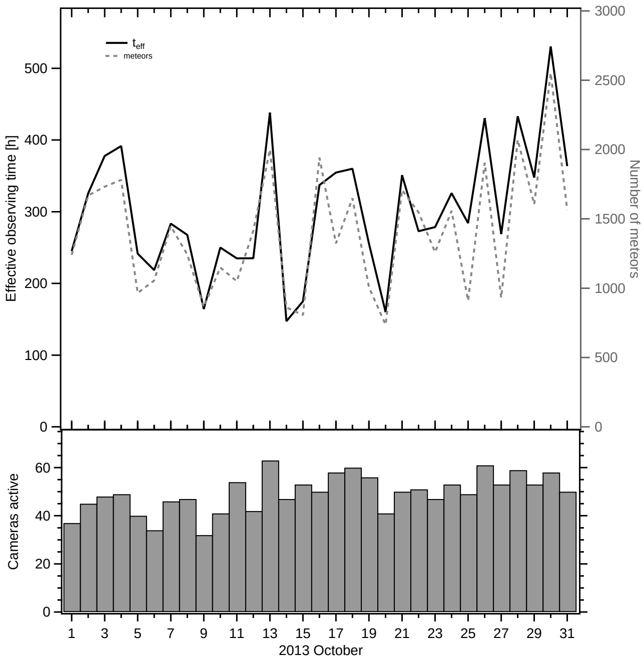

Figure 1 – Monthly summary for the effective observing time (solid black line), number of meteors (dashed gray line) and number of cameras active (bars) in 2013 October.

Figure 2 – The four remotely operated cameras Remo1 to Remo4 at the roof in Ketzür.

2 Orionids

The most important meteor shower of October are the Orionids, which had two obstacles this year. First, their maximum occurred just after the full Moon, so that the night sky was brightly illuminated. Also, the years of enhanced activity when we could enjoy zenithal hourly rates greater than 50 are over. The shower has settled at the normal activity level in agreement with the predictions. Figure 3 compares the flux density profiles of the last three years. Whereas in 2011 peak flux densities

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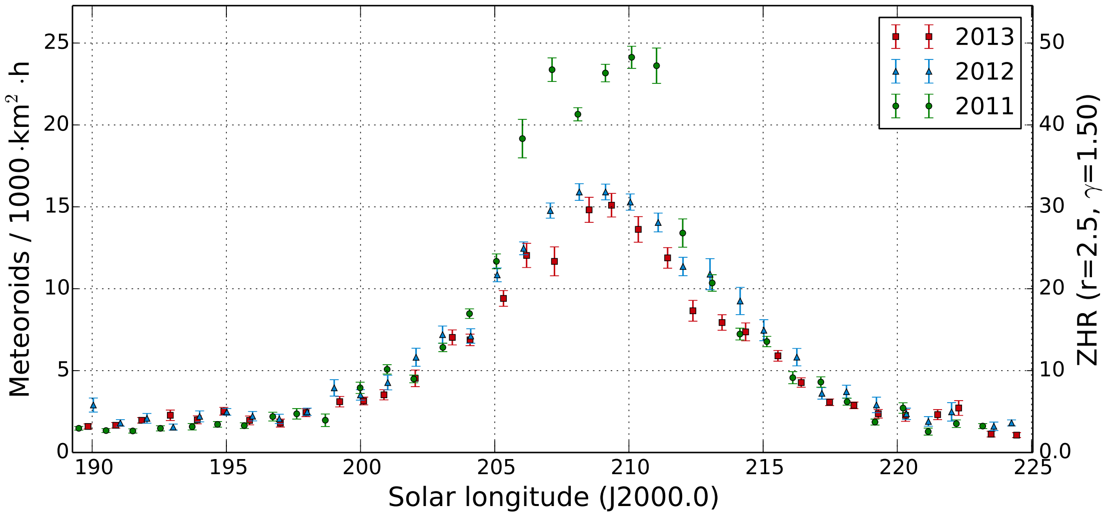

Figure 3 – Flux density profile of the Orionids in the years 2011 to 2013.

of 25 were still reached, the activity profiles of 2012 and 2013 largely coincide with peak values of about 15 meteoroids per 1 000 km^2 per hour (at a zenith exponent of $\gamma = 1.5$).

2.1 Population index

The Orionids presented a second chance to test and optimize the new procedure for determination of the population index (Molau et al., 2013b). The circumstances were less optimal, though, since hardly any camera enjoyed good observing conditions. Either the Moon crossed the field of view and blinded the cameras, or it was partly clouded.

Still, we recomputed the flux density profiles as a function of the population index for each camera, and plotted them. The result was disastrous: even in the logarithmic presentation, the curves deviated largely from one another. In addition, they were often more or less parallel, since the limiting magnitude of all cameras was similarly poor. There was no sensible point of intersection between these curves.

For this reason we improved the algorithm. Even powerful cameras had phases with poor observing conditions, where the limiting Orionid magnitude was hardly better than magnitude +2. So instead of plotting the dependency of the flux density on the population index for each camera, we accumulated the data according to the Orionid limiting magnitude. For each observing minute and each camera we determined to which limiting magnitude bin (+1 to +5 magnitude) the minute belongs, and then we accumulated the meteor count and the effective collection area (as a function of the population index). In the end, those two numbers were divided.

As expected the resulting curves show a larger angle of intersection: at a limiting magnitude of +6.5, the population index has no impact on the flux density, and we would see a horizontal line in the diagram. The greater the limiting magnitude deviates from +6.5, the larger is the impact of the population index and the steeper are the curves. A larger intersection angle, however, allows for a better determination of the point of intersection and thereby the population index.

We can see immediately that the procedure is working in principle – the curves show a more or less well-defined intersection point. At closer inspection we notice the following details:

- October 21/22 (upper left): All five curves intersect in a relatively compact interval between 2.0 and 2.5. The population index with the lowest variance of log probabilities is $r = 2.2$.
- October 22/23 (upper right): The curves intersect at a population index of $r = 2.5$. The magnitude +2 curve deviates slightly towards lower values, the magnitude +3 curve deviates even more.
- October 23/24 (lower left): Once more there is a relatively well-defined intersection point at a population index of $r = 2.4$. This time the magnitude +5 curve slightly deviates, but that curve is based on the smallest data set.
- October 24/25 (lower right): The curves have an intersection point at a population index of $r = 2.1$, but once more the magnitude +3 curve deviates noticeably downwards.

If it was the curve at the low or high end of the limiting magnitude spectrum it would be easy to explain the deviations. However, it is currently not clear why just the magnitude +3 curve with the biggest data set deviates the most.

In search for an explanation we analysed whether individual cameras would cause this effect. In addition, we repeated the analysis using only the "good intervals", when the limiting magnitude was no more than 1 magnitude below the best limiting magnitude of that camera in a particular night (to exclude side effects by

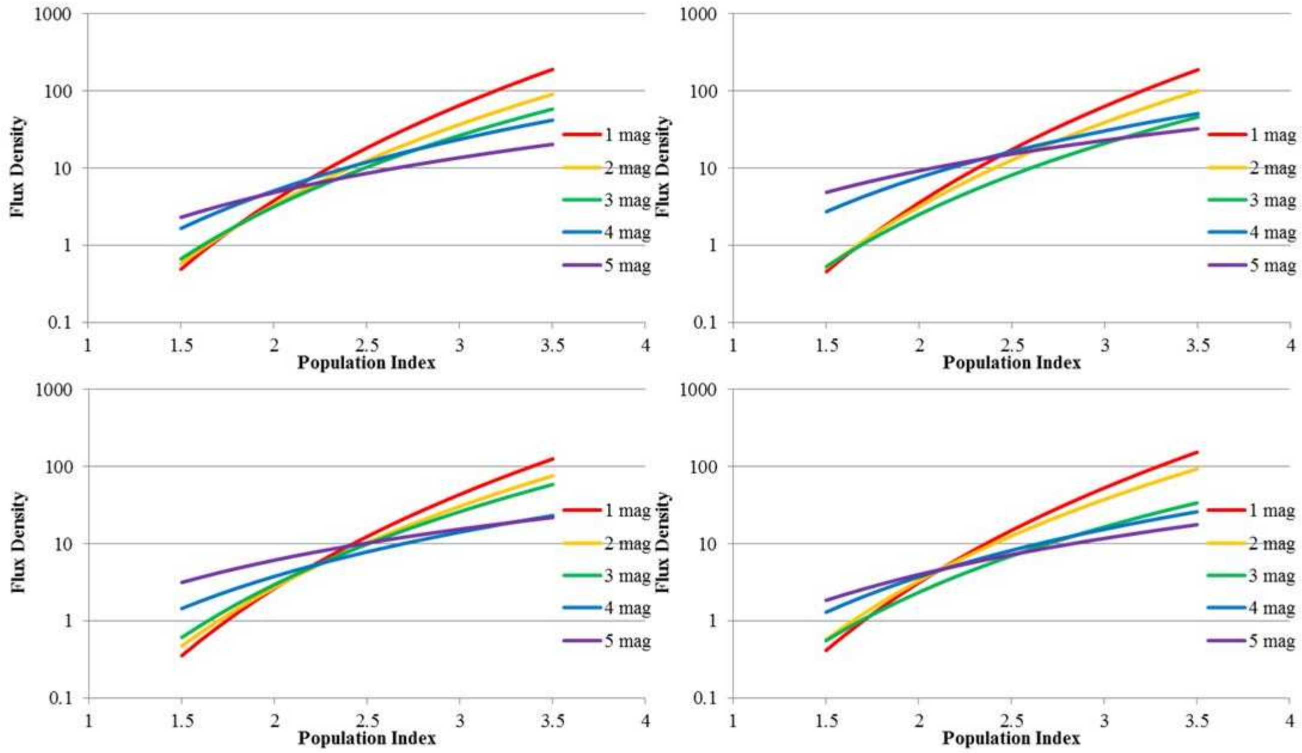

Figure 4 – Dependency of the flux density from the population index, determined for different Orionid limiting magnitude bins over all active cameras. Shown are the values for the nights of October 21/22 (upper left graph) to 24/25 (lower right graph).

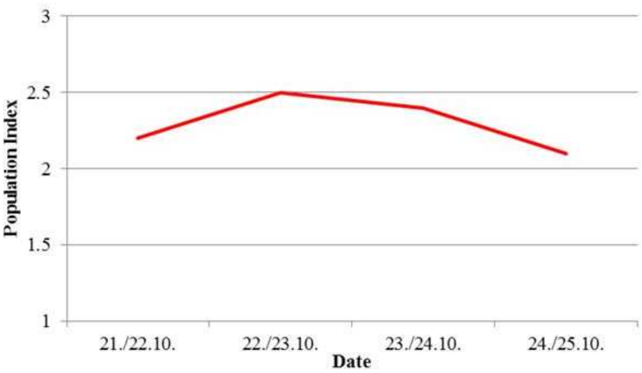

Figure 5 – Population index profile of the Orionids between 2013 October 21/22 and 24/25.

the clouds and the Moon). In the latter case, the r-values tended to be a little larger, but the overall appearance did not change qualitatively.

For the population index we determined from each graph the r-value for which the variance of the log flux densities was smallest, i.e. where the curves in Figure 4 were closest to each other. The resulting profile is presented in Figure 5.

We can conclude that the population index can be determined with the described method. However, it is still not clear how good our values agree with the r-values obtained from visual observations, since there is no analysis of visual Orionid data from 2013 available yet. At least, the range that we determined is not atypical for this shower.

We hope that the observed discrepancies in the intersection point of the curves vanish when a better data set (fewer clouds, no Moon) is available. In addition, we should not forget that we are still at an early stage of the population index analysis. In the future we will probably see further improvements in the calculation routine.

References

Molau S., Kac J., Berko E., Crivello S., Stomeo E., Igaz A., Barentsen G., and Goncalves R. (2013a). "Results of the IMO Video Meteor Network – October 2012". *WGN, Journal of the IMO*, **41:1**, 23–30.

Molau S., Kac J., Crivello S., Stomeo E., Barentsen G., and Goncalves R. (2013b). "Results of the IMO Video Meteor Network – August 2013". *WGN, Journal of the IMO*, **41:6**, 201–206.

Handling Editor: Javor Kac

Table 1 – Observers contributing to 2013 October data of the IMO Video Meteor Network. Eff.CA designates the effective collection area.

Code	Name	Place	Camera	FOV [°²]	Stellar LM [mag]	Eff.CA [km²]	Nights	Time [h]	Meteors
ARLRA	Arlt	Ludwigsfelde/DE	Ludwig1 (0.8/8)	1488	4.8	726	16	122.2	203
BANPE	Bánfalvi	Zalaegerszeg/HU	Huvcse01 (0.95/5)	2423	3.4	361	14	76.4	278
BASLU	Bastiaens	Hove/BE	Urania1 (0.8/3.8)*	4545	2.5	237	12	41.9	49
BERER	Berkó	Ludányhalászi/HU	Hulud1 (0.8/3.8)	5542	4.8	3847	24	187.4	1219
			Hulud2 (0.95/4)	3398	3.8	671	24	182.0	454
			Hulud3 (0.95/4)	4357	3.8	876	23	172.1	259
BOMMA	Bombardini	Faenza/IT	Mario (1.2/4.0)	5794	3.3	739	20	100.9	630
BREMA	Breukers	Hengelo/NL	Mbb3 (0.75/6)	2399	4.2	699	16	94.5	349
			Mbb4 (0.8/8)	1470	5.1	1208	10	43.1	113
BRIBE	Klemt	Herne/DE	Hermine (0.8/6)	2374	4.2	678	26	110.9	442
		Bergisch Gladbach/DE	Klemoi (0.8/6)	2286	4.6	1080	24	116.8	502
CRIST	Crivello	Valbrevenna/IT	Bilbo (0.8/3.8)	5458	4.2	1772	22	79.8	379
			C3P8 (0.8/3.8)	5455	4.2	1586	23	91.2	385
			Stg38 (0.8/3.8)	5614	4.4	2007	24	90.1	416
DONJE	Donani	Faenza/IT	Jenni (1.2/4)	5886	3.9	1222	20	119.9	691
ELTMA	Eltri	Venezia/IT	Met38 (0.8/3.8)	5631	4.3	2151	13	53.9	221
GONRU	Goncalves	Tomar/PT	Templar1 (0.8/6)	2179	5.3	1842	19	166.1	857
			Templar2 (0.8/6)	2080	5.0	1508	21	170.6	640
			Templar3 (0.8/8)	1438	4.3	571	22	164.1	573
			Templar4 (0.8/3.8)	4475	3.0	442	20	159.8	564
GOVMI	Govedič	Središče ob Dravi/SI	Orion2 (0.8/8)	1447	5.5	1841	24	181.1	922
			Orion3 (0.95/5)	2665	4.9	2069	21	144.2	361
			Orion4 (0.95/5)	2662	4.3	1043	26	176.5	498
HINWO	Hinz	Brannenburg/DE	Acr (2.0/35)*	557	7.3	5002	21	116.2	662
IGAAN	Igaz	Baja/HU	Hubaj (0.8/3.8)	5552	2.8	403	27	154.0	514
		Debrecen/HU	Hudeb (0.8/3.8)	5522	3.2	620	26	190.5	572
		Hódmezővásárhely/HU	Huhod (0.8/3.8)	5502	3.4	764	27	192.6	511
		Budapest/HU	Hupol (1.2/4)	3790	3.3	475	26	163.5	153
JONKA	Jonas	Budapest/HU	Husor (0.95/4)	2286	3.9	445	25	185.8	409
KACJA	Kac	Ljubljana/SI	Orion1 (0.8/8)	1402	3.8	331	15	41.0	77
		Kamnik/SI	Cvetka (0.8/3.8)*	4914	4.3	1842	15	76.2	516
			Rezika (0.8/6)	2270	4.4	840	14	71.9	577
			Stefka (0.8/3.8)	5471	2.8	379	16	86.5	354
		Kostanjevec/SI	Metka (0.8/12)*	715	6.4	640	4	27.8	181
KERST	Kerr	Glenlee/AU	Gocam1 (0.8/3.8)	5189	4.6	2550	9	35.7	128
KISSZ	Kiss	Sülysáp/HU	Husul (0.95/5)*	4295	3.0	355	26	135.1	171
KOSDE	Koschny	Izana Obs./ES	Icc7 (0.85/25)*	714	5.9	1464	29	233.6	3020
		La Palma/ES	Icc9 (0.85/25)*	683	6.7	2951	27	209.3	2653
		Noordwijkerhout/NL	Lic4 (1.4/50)*	2027	6.0	4509	21	132.9	694

Table 1 – Observers contributing to 2013 October data of the IMO Video Meteor Network – continued from previous page.

Code	Name	Place	Camera	FOV [°²]	Stellar LM [mag]	Eff.CA [km²]	Nights	Time [h]	Meteors
MACMA	Maciejewski	Chelm/PL	Pav35 (0.8/3.8)	5495	4.0	1584	17	119.3	493
			Pav36 (0.8/3.8)*	5668	4.0	1573	22	116.6	393
			Pav43 (0.75/4.5)*	3132	3.1	319	23	112.6	242
			Pav60 (0.75/4.5)	2250	3.1	281	17	64.3	144
MARGR	Maravelias	Lofoupoli-Crete/GR	Loomecon (0.8/12)	738	6.3	2698	25	219.8	664
MASMI	Maslov	Novosibirsk/RU	Nowatec (0.8/3.8)	5574	3.6	773	13	70.8	663
MOLSI	Molau	Seysdorf/DE	Avis2 (1.4/50)*	1230	6.9	6152	26	176.6	1938
			Mincam1 (0.8/8)	1477	4.9	1084	25	172.6	621
		Ketzür/DE	Remo1 (0.8/8)	1467	6.5	5491	26	186.1	1745
			Remo2 (0.8/8)	1478	6.4	4778	25	195.6	1232
			Remo3 (0.8/8)	1420	5.6	1967	22	171.5	304
			Remo4 (0.8/8)	1478	6.5	5358	22	164.3	1328
MORJO	Morvai	Fülöpszállás/HU	Huful (1.4/5)	2522	3.5	532	29	219.9	586
OCHPA	Ochner	Albiano/IT	Albiano (1.2/4.5)	2944	3.5	358	3	17.1	62
OTTMI	Otte	Pearl City/US	Orie1 (1.4/5.7)	3837	3.8	460	25	166.0	746
PERZS	Perkó	Becsehely/HU	Hubec (0.8/3.8)*	5498	2.9	460	24	148.7	1125
PUCRC	Pucer	Nova vas nad Dragonjo/SI	Mobcam1 (0.75/6)	2398	5.3	2976	14	69.8	333
ROTEC	Rothenberg	Berlin/DE	Armefa (0.8/6)	2366	4.5	911	19	147.0	377
SARAN	Saraiva	Carnaxide/PT	Ro1 (0.75/6)	2362	3.7	381	21	162.6	488
			Ro2 (0.75/6)	2381	3.8	459	12	105.0	325
			Sofia (0.8/12)	738	5.3	907	19	165.5	368
SCALE	Scarpa	Alberoni/IT	Leo (1.2/4.5)*	4152	4.5	2052	7	37.8	111
SCHHA	Schremmer	Niederkrüchten/DE	Doraemon (0.8/3.8)	4900	3.0	409	27	137.5	576
SLAST	Slavec	Ljubljana/SI	Kayak1 (1.8/28)	563	6.2	1294	7	16.5	63
STOEN	Stomeo	Scorze/IT	Min38 (0.8/3.8)	5566	4.8	3270	25	68.7	468
			Noa38 (0.8/3.8)	5609	4.2	1911	24	69.8	368
			Sco38 (0.8/3.8)	5598	4.8	3306	23	68.1	548
STORO	Štork	Ondřejov/CZ	Ond1 (1.4/50)*	2195	5.8	4595	2	17.0	505
STRJO	Strunk	Herford/DE	Mincam2 (0.8/6)	2354	5.4	2571	22	111.2	536
			Mincam3 (0.8/12)	2338	5.5	3590	24	124.4	677
			Mincam4 (1.0/2.6)	9791	2.7	552	22	93.7	287
			Mincam5 (0.8/6)	2349	5.0	1896	24	119.6	501
TEPIS	Tepliczky	Agostyán/HU	Huago (0.75/4.5)	2427	4.4	1036	27	171.4	578
		Budapest/HU	Humob (0.8/6)	2388	4.8	1607	29	181.5	859
TRIMI	Triglav	Velenje/SI	Sraka (0.8/6)*	2222	4.0	546	18	112.8	420
YRJIL	Yrjölä	Kuusankoski/FI	Finexcam (0.8/6)	2337	5.5	3574	15	101.2	533
ZELZO	Zelko	Budapest/HU	Huvcse03 (1.0/4.5)	2224	4.4	933	10	48.3	143
						Overall	31	9 349.3	43 547

* active field of view smaller than video frame

Results of the IMO Video Meteor Network — November 2013

Sirko Molau,[1] *Javor Kac,*[2] *Stefano Crivello,*[3] *Enrico Stomeo,*[4] *Geert Barentsen,*[5] *and Rui Goncalves*[6]

Preliminary results for November 2013 are presented of the IMO Video Meteor Network data, obtained by 70 cameras of the Network. Flux density profile is presented for the 2013 Leonids. Using a refined procedure for population index calculation, the population index profile is also presented.

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1 Introduction

November 2013 was a month with poor weather – not as bad as November 2012, but much worse than November 2011. Observers in Germany, Italy and at the Iberian peninsula were still in a comfortable position, but in particular in Hungary and Slovenia observation was no fun. Only 19 out of 70 cameras obtained twenty and more observing nights. The effective observing time accumulated to 6 700 hours, roughly one hundred more than in the previous year. The number of meteors increased by 2 000 to over 29 000 (Table 1 and Figure 1).

With Thomas Łojek, we could count a second Polish observer for the IMO Network. Tomasz operates the station PAV57 of the Polish fireball network, a Tayama camera with $f/1.0$ zoom lens and a focal length of ~ 5 mm.

2 Leonids

Let us have a look at the highlights of November. The golden years of the Leonids are over – the last meteor storm dates back more than ten years. Still, the activity profiles show variations from one year to the next as depicted in Figure 2. Whereas the data of the last three years agree perfectly at the ascending branch until 234° solar longitude, there are larger deviations between the individual years thereafter. In 2012, the flux density did not exceed 8 meteoroids per 1 000 km^2 per hour. In 2011 and 2013, however, peak activity was 50% higher.

It remains to be checked if the chosen population index of 2.5 was realistic. To find out, we wanted to apply the same procedure as for the Orionids (Molau et al., 2014). However, there are certain situations where the procedure requires further refinement.

2.1 Population index calculation refined

Let us go back to the Orionid night of 2013 October 20/21, when a limiting magnitude interval from +1 to +5 magnitude was covered (Figure 3, left). Most lines show a relatively well-defined intersection point, but the magnitude +5 line deviates strongly. The reason could be that the data set was too small (45 minutes observing time, one meteor), but should that line be completely omitted? And when should we omit such an interval?

The problem can be formulated in a different manner: We want to find the point where the lines are closest to each other. We do that by handling the lines not as strictly focused, but we blur them mathematically (as depicted schematically in Figure 3, right) and choose the r-value, where the overlapping intensity is highest.

But shall all lines be blurred in the same way, or do some lines have to be blurred stronger than others? Instead of omitting the magnitude +5 line, we could give it a lower weight in the average by blurring it more than other lines.

This approach was implemented by us. Even though the following derivation starts from a different perspective, it yields in the end no more than a probabilistic weighting of lines when the best intersection point is determined.

Now for the mathematical derivation: Let us have a look at the October 20/21 data set as a whole. We

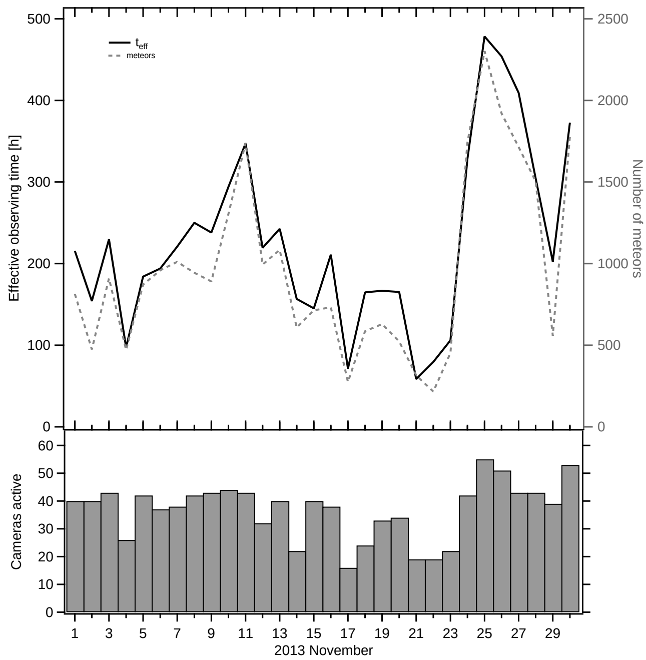

Figure 1 – Monthly summary for the effective observing time (solid black line), number of meteors (dashed gray line) and number of cameras active (bars) in 2013 November.

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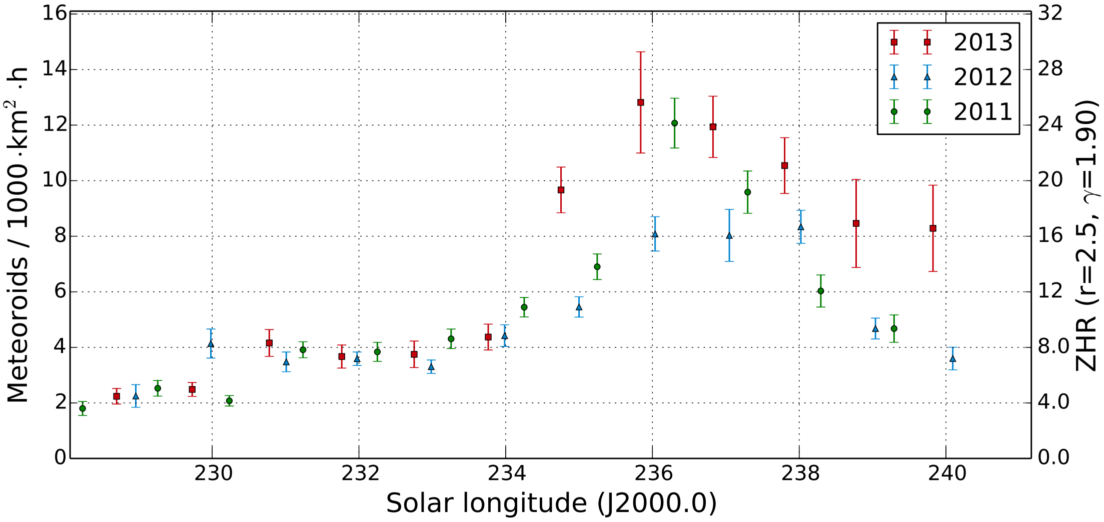

Figure 2 – Flux density profile of the Leonids in the years 2011 till 2013.

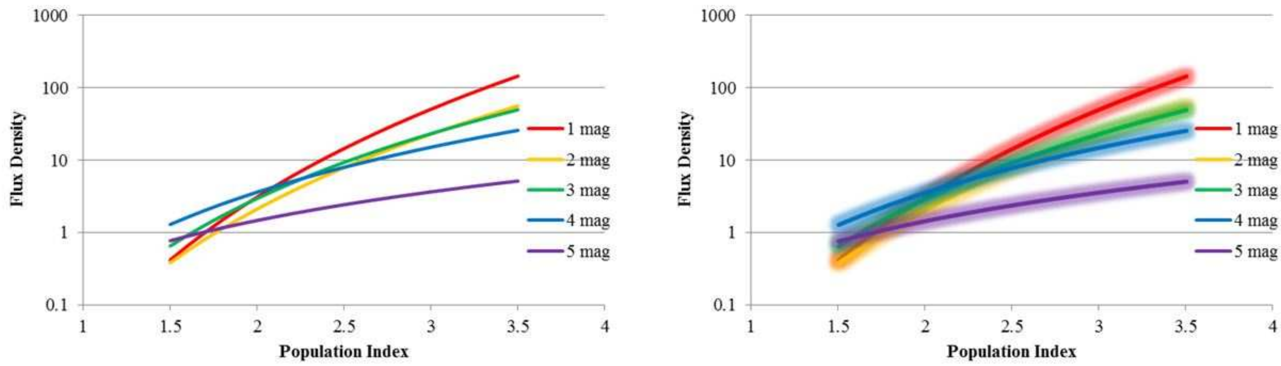

Figure 3 – To determine the population index, we plot the dependency of the flux density from the r-value for different limiting magnitudes (left). To determine the best intersection point, the lines are mathematically blurred (right).

observed 170 Orionids with an effective collection area of 18 000 km^2 per hour. The population index describes the brightness distribution, i.e. it defines how many of these 170 meteors belong to the first to fifth magnitude. In our example, we do not look at meteors of magnitude x, but rather at meteors with variable magnitudes recorded when the limiting magnitude was x. Still, the distribution is governed by the population index. Given the r-value we know the effective collection area of each limiting magnitude interval. Thus we know, how many meteors out of the 170 should fall into each class. This is depicted in Figure 4 with solid lines. Expectedly, intervals with poor limiting magnitude (red and yellow lines) perform much better at low r-values (i.e. when there are many bright meteors) than at large r-values (many faint meteors).

In addition, Figure 4 shows with dashed lines the real number of meteors that were observed in each limiting magnitude interval. Again, they sum up to 170.

So far it seems we did not gain a lot, since again we have different intersection points between the corresponding lines, but now we can introduce a well-established stochastic model. Here we are dealing with a classical Poisson distribution.

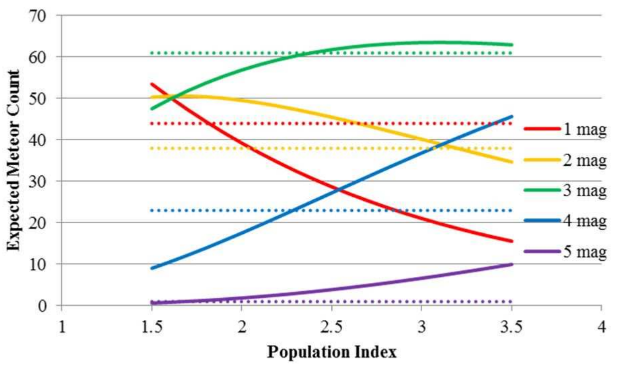

Figure 4 – Comparison of the expected (solid line) and the observed (dashed line) number of Orionids at different limiting magnitudes.

So what is a Poisson distribution? Let us look at random events, which occur independently of each other with a constant rate of λ, e.g. how many persons enter a department store on a Saturday afternoon. The average λ may be 600 persons per hour. That does not mean, of course, that every minute exactly 10 persons enter the front door. The number is fluctuating from one minute to the next, because they are independent stochastic

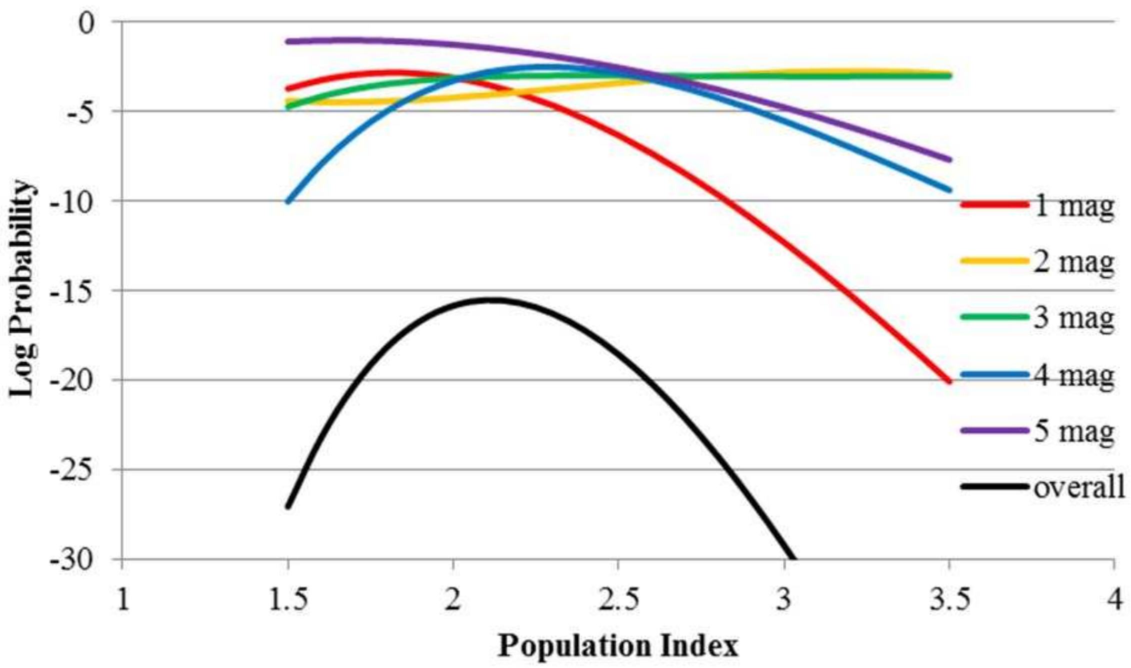

Figure 5 – With the Poisson distribution we can calculate the probability of the observed number of meteors given the expected number of meteors. The lower line represents the combined probability over all limiting magnitude intervals.

events. The Poisson distribution $P_\lambda(k) = {}^{\lambda^k}/_{k!} \cdot e^{-\lambda}$ describes the probability that exactly k persons enter the department store in one minute. With a 12.5% chance it will be ten persons, but it may also happen that only two (0.2%) or even 15 customer (3.5%) enter the store. The probability of such outliers is low, but not zero.

The same Poisson distribution holds for the number of meteors observed per unit time at a constant meteor activity. Let us assume that an average of $\lambda = 60$ Orionids per hour show up. The probability that no meteor is seen at one minute is as high as the chance to see one meteor (37%). Five meteors a minute are unlikely (0.3%), but still it happens sometimes.

Back to the meteor count per brightness class: We can calculate for each limiting magnitude and each population index the expected meteor count λ, and we know the truly observed meteor count k. The Poisson distribution tells us how probable that pair is.

The Poisson distribution reflects two important properties. On the one hand, it automatically incorporates the size of the data set: If only one meteor is expected, the probability of observing 0, 1 or 2 meteors is nearly the same. Hence, this limiting magnitude interval will play an underpart in the determination of the population index. If at an interval with plenty of data 50 meteors are expected, then the probability to observe 40 or 60 meteors is much smaller. This interval will define the r-value much better.

On the other hand we see that the meteor count alone is not the only criterion. At an average limiting magnitude of magnitude +3, for example, the number of expected meteors is relatively independent of the population index. We can vary the r-value, but the number of meteors observed at a limiting magnitude of +3 will differ only little. Hence, this interval is less valuable to determine the population index.

Figure 5 shows the dependency of the observed meteor count from the population index using the example data set of October 20/21. Probabilities are presented as logarithmic values, because they easily become very small. The lower black line is the product of the individual probabilities resp. the sum of the log probabilities. It represents the resulting probability for each population index and yields the best r-value. Beyond that, is defines also the quality of the estimate: If the overall log probability is relatively large (close to 0), then the maxima of different curves agree well. If it is smaller, then each of the individual limiting magnitude intervals yields a different picture. If the peak is spiky (independent of the absolute value), then the data set is discriminative and the r-value can be determined quite precisely. If it is shallow, then the observed brightness range was too small to yield a precise r-value.

The calculation is done in discrete r-value steps of 0.1. To increase the resolution, we fit a quadratic function $ax^2 + bx + c$ to the five values centered at the peak. That can be easily differentiated and the zero crossing of the derivative (= r-value with highest probability) is given by $b/2a$. In addition we can calculate a confidence interval, e.g. which r-values have still at least 50% of the peak probability. In the example of Figure 5, the best population index is 2.12, and all values between 1.96 and 2.29 are in the 50% range.

Let us summarize: With the modified procedure we find the best intersection point between the lines of different limiting magnitude (Figure 3). It incorporates the size of the data set and how well the limiting magnitude class suits at all to determine the population index. If the data set is small or if the expected meteor number changes only little for different r-values, then the class has a smaller weight in the calculation then other. We do not have to arbitrarily omit limiting mag-

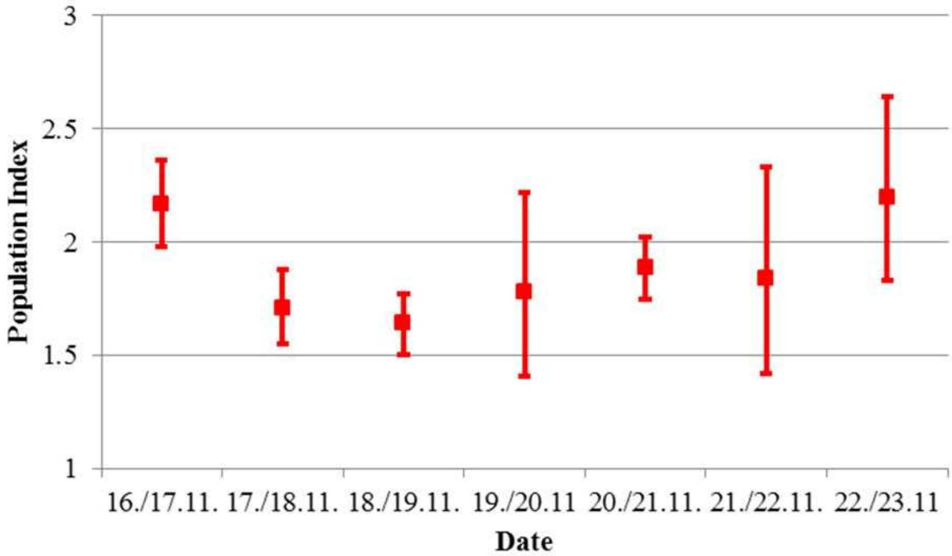

Figure 6 – Population index profile of the Leonids 2013.

nitude intervals, which makes this method quite reliable from the stochastic point of view.

It remains to be clarified if all data sets should be used for the determination of the r-value or not. It could be that cloudy intervals distort the result systematically, since the limiting magnitude is averaged over the full field of view. Equally we may introduce errors with cameras that show a systematic deviation in the limiting magnitude calculation (e.g. because of poor reference stars). Last but not least, the choice of the brightness intervals was arbitrary. Maybe we get better precision if we do not use fixed one-magnitude intervals but rather adapt the interval boundaries dynamically to the available data set? All these aspects require further investigations in the future.

2.2 Population index of the 2013 Leonids

After so much theory, let us finally have a look at the outcome when the modified approach is applied to the Leonid 2013 data set (Figure 6). The values from November 16/17 to 18/19 and on November 20/21 have a small variance, for all other nights the data set was simply too small to determine the r-value precisely. Overall, the population index is smaller than two, but there is still no independent confirmation from visual observations.

References

Molau S., Kac J., Crivello S., Stomeo E., Barentsen G., and Goncalves R. (2014). “Results of the IMO Video Meteor Network – October 2013”. *WGN, Journal of the IMO*, **42:1**, 20–24.

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Table 1 – Observers contributing to 2013 November data of the IMO Video Meteor Network. Eff.CA designates the effective collection area.

Code	Name	Place	Camera	FOV [°2]	Stellar LM [mag]	Eff.CA [km2]	Nights	Time [h]	Meteors
ARLRA	Arlt	Ludwigsfelde/DE	LUDWIG1 (0.8/8)	1488	4.8	726	6	56.4	63
BANPE	Bánfalvi	Zalaegerszeg/HU	HUVCSE01 (0.95/5)	2423	3.4	361	8	48.9	155
BERER	Berkó	Ludányhalászi/HU	HULUD1 (0.8/3.8)	5542	4.8	3847	6	47.2	244
			HULUD2 (0.95/4)	3398	3.8	671	6	43.4	93
			HULUD3 (0.95/4)	4357	3.8	876	6	45.0	59
BOMMA	Bombardini	Faenza/IT	MARIO (1.2/4.0)	5794	3.3	739	18	84.7	414
BREMA	Breukers	Hengelo/NL	MBB3 (0.75/6)	2399	4.2	699	14	45.0	141
BRIBE	Klemt	Herne/DE	HERMINE (0.8/6)	2374	4.2	678	2	11.4	48
		Bergisch Gladbach/DE	KLEMOI (0.8/6)	2286	4.6	1080	14	52.2	208
CRIST	Crivello	Valbrevenna/IT	BILBO (0.8/3.8)	5458	4.2	1772	25	162.5	808
			C3P8 (0.8/3.8)	5455	4.2	1586	23	166.8	619
			STG38 (0.8/3.8)	5614	4.4	2007	23	166.6	855
DONJE	Donani	Faenza/IT	JENNI (1.2/4)	5886	3.9	1222	16	97.6	400
ELTMA	Eltri	Venezia/IT	MET38 (0.8/3.8)	5631	4.3	2151	8	67.4	284
GONRU	Goncalves	Tomar/PT	TEMPLAR1 (0.8/6)	2179	5.3	1842	23	226.9	1047
			TEMPLAR2 (0.8/6)	2080	5.0	1508	23	239.4	1045
			TEMPLAR3 (0.8/8)	1438	4.3	571	26	255.7	967
			TEMPLAR4 (0.8/3.8)	4475	3.0	442	23	232.5	908
GOVMI	Govedič	Središče ob Dravi/SI	ORION2 (0.8/8)	1447	5.5	1841	14	63.4	210
			ORION3 (0.95/5)	2665	4.9	2069	9	40.4	85
			ORION4 (0.95/5)	2662	4.3	1043	13	54.3	108
HINWO	Hinz	Schwarzenberg/DE	ACR (2.0/35)*	557	7.3	5002	13	67.1	356
IGAAN	Igaz	Baja/HU	HUBAJ (0.8/3.8)	5552	2.8	403	12	25.7	89
		Debrecen/HU	HUDEB (0.8/3.8)	5522	3.2	620	17	92.8	210
		Hódmezővásárhely/HU	HUHOD (0.8/3.8)	5502	3.4	764	17	71.2	157
		Budapest/HU	HUPOL (1.2/4)	3790	3.3	475	14	68.2	55
JONKA	Jonas	Budapest/HU	HUSOR (0.95/4)	2286	3.9	445	14	69.3	151
KACJA	Kac	Ljubljana/SI	ORION1 (0.8/8)	1402	3.8	331	6	24.5	58
		Kamnik/SI	CVETKA (0.8/3.8)*	4914	4.3	1842	6	40.5	265
			STEFKA (0.8/3.8)	5471	2.8	379	7	42.9	227
KERST	Kerr	Glenlee/AU	GOCAM1 (0.8/3.8)	5189	4.6	2550	15	81.7	240
KISSZ	Kiss	Sülysáp/HU	HUSUL (0.95/5)*	4295	3.0	355	18	56.7	75
KOSDE	Koschny	Izana Obs./ES	ICC7 (0.85/25)*	714	5.9	1464	26	221.2	1846
		La Palma/ES	ICC9 (0.85/25)*	683	6.7	2951	21	144.9	1560
		Noordwijkerhout/NL	LIC4 (1.4/50)*	2027	6.0	4509	15	72.4	209
LOJTO	Łojek	Grabniak/PL	PAV57 (1.0/5)	1631	3.5	269	8	37.9	83

Table 1 – Observers contributing to 2013 November data of the IMO Video Meteor Network – continued from previous page.

Code	Name	Place	Camera	FOV [°²]	Stellar LM [mag]	Eff.CA [km²]	Nights	Time [h]	Meteors
MACMA	Maciejewski	Chelm/PL	Pav35 (0.8/3.8)	5495	4.0	1584	17	77.4	314
			Pav36 (0.8/3.8)*	5668	4.0	1573	18	72.4	274
			Pav43 (0.75/4.5)*	3132	3.1	319	15	56.0	152
			Pav60 (0.75/4.5)	2250	3.1	281	16	38.5	159
MARGR	Maravelias	Lofoupoli-Crete/GR	Loomecon (0.8/12)	738	6.3	2698	19	136.7	377
MASMI	Maslov	Novosibirsk/RU	Nowatec (0.8/3.8)	5574	3.6	773	8	39.3	273
MOLSI	Molau	Seysdorf/DE	Avis2 (1.4/50)*	1230	6.9	6152	17	100.5	1056
			Mincam1 (0.8/8)	1477	4.9	1084	17	90.1	325
		Ketzür/DE	Remo1 (0.8/8)	1467	6.5	5491	21	117.4	810
			Remo2 (0.8/8)	1478	6.4	4778	22	125.2	622
			Remo3 (0.8/8)	1420	5.6	1967	16	110.7	179
			Remo4 (0.8/8)	1478	6.5	5358	20	125.3	859
MORJO	Morvai	Fülöpszállás/HU	Huful (1.4/5)	2522	3.5	532	18	82.1	177
OCHPA	Ochner	Albiano/IT	Albiano (1.2/4.5)	2944	3.5	358	13	83.3	240
OTTMI	Otte	Pearl City/US	Orie1 (1.4/5.7)	3837	3.8	460	24	138.1	628
PERZS	Perkó	Becsehely/HU	Hubec (0.8/3.8)*	5498	2.9	460	17	95.8	597
ROTEC	Rothenberg	Berlin/DE	Armefa (0.8/6)	2366	4.5	911	14	99.7	212
SARAN	Saraiva	Carnaxide/PT	Ro1 (0.75/6)	2362	3.7	381	24	225.6	676
			Ro2 (0.75/6)	2381	3.8	459	24	216.8	745
			Sofia (0.8/12)	738	5.3	907	23	224.7	568
SCALE	Scarpa	Alberoni/IT	Leo (1.2/4.5)*	4152	4.5	2052	5	29.3	75
SCHHA	Schremmer	Niederkrüchten/DE	Doraemon (0.8/3.8)	4900	3.0	409	18	79.9	236
SLAST	Slavec	Ljubljana/SI	Kayak1 (1.8/28)	563	6.2	1294	8	48.3	108
STOEN	Stomeo	Scorze/IT	Min38 (0.8/3.8)	5566	4.8	3270	25	142.9	985
			Noa38 (0.8/3.8)	5609	4.2	1911	24	146.3	843
			Sco38 (0.8/3.8)	5598	4.8	3306	23	135.4	1164
STRJO	Strunk	Herford/DE	Mincam2 (0.8/6)	2354	5.4	2751	15	73.5	311
			Mincam3 (0.8/12)	2338	5.5	3590	18	82.3	280
			Mincam4 (1.0/2.6)	9791	2.7	552	17	61.3	132
			Mincam5 (0.8/6)	2349	5.0	1896	16	72.9	237
TEPIS	Tepliczky	Agostyán/HU	Huago (0.75/4.5)	2427	4.4	1036	10	77.9	221
		Budapest/HU	Humob (0.8/6)	2388	4.8	1607	17	72.6	369
TRIMI	Triglav	Velenje/SI	Sraka (0.8/6)*	2222	4.0	546	15	81.7	189
YRJIL	Yrjölä	Kuusankoski/FI	Finexcam (0.8/6)	2337	5.5	3574	14	78.0	307
						Overall	30	6 762.6	29 042

* active field of view smaller than video frame

History

Meteor Beliefs Project: Meteors in the Māori astronomical traditions of New Zealand

Tui R. Britton[1] *and Duane W. Hamacher*[2]

We review the literature for perceptions of meteors in the Māori culture of Aotearoa or New Zealand. We examine representations of meteors in religion, story, and ceremony. We find that meteors are sometimes personified as gods or children, or are seen as omens of death and destruction. The stories we found highlight the broad perception of meteors found throughout the Māori culture, and note that some early scholars conflated the terms *comet* and *meteor*.

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"The sparks of Rongomai never fail to bring shouts of wonder from the lips of men"

A description of a Māori ancestor taking the form of a bright meteor (Kingsley-Smith, 1967).

1 Introduction

The Māori of New Zealand (Aotearoa) are a Polynesian people who descend from the Cook Island Māori and other Eastern Polynesian groups (King, 2003). The Māori migrated to Aotearoa in the 13th century, travelling by *waka* (canoe) from Rarotonga (Anderson, 2009; Walter & Moeka'a, 2000). This Great Migration comprised seven or eight wakas[a] containing the ancestors of the present day Māori people of Aotearoa (Evans, 2009). Many Māori can trace their lineage back to one or more of the original waka.

The arrival of Europeans (*Pakeha*[b]) in the late 18th century marked a change in Māori culture. The Māori quickly learnt to read and write, being introduced to these new skills from the Pakeha. The Māori embraced these skills, in order to preserve their knowledge and oral traditions. Countless documents exist written by both Māori and Pakeha that contain the knowledge of the Māori. Researchers are still tracking down and sifting through these documents for many aspects relating to Māori culture, particularly astronomy (e.g. Harris et al., 2013; Orchiston, 2000).

We present here a brief examination of the cultural knowledge of Māori astronomy by focusing on their myths and legends of meteors or shooting stars. We examine many well-known records for references to meteors in story, religion, and ceremony. The majority of published information about Māori astronomical traditions, including meteor names, comes from the work of Elsdon Best (1955). His published study of Māori astronomy remains the most detailed and comprehensive to date.

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[a]There is some contention over the exact number of waka and the island(s) from which they set out on their journey.

[b]Pakeha is not a derogatory term and is used colloquially to refer to anyone of European descent.

2 Meteor Names

In Aotearoa, meteors have many names, varying from region to region. In the Bay of Plenty, meteors are known as *matakōkiri* (the darting ones), *tūmatakōkiri*, *kōtiri*, *kōtiritiri*, *tamarau*, and possibly *unahi o Taero* (Stowell, 1911, p. 199; Best, 1955, p. 69). The Ngatiawa tribe near Whakatane say that *Taneatua* – the *tohunga* (priest) of the Mataatua (one of the seven original waka) – brought comets and meteors with him on the Great Migration and released them into the southern skies (Kingsley-Smith, 1967). The Ngatiawa call these meteors *Rongomai*, a name also used to denote a comet – in particular Halley's Comet (Stowell, 1911, p. 200).

3 Perceptions of Meteors

Perceptions of meteors were diverse among the Māori. Meteors were generally seen as omens of evil or death (Best, 1955; Mackrell, 1985, pp. 21–28). A meteor may portend the death, or the rise and fall, of a chief (Best, 1955, p. 70). Meteors were also viewed as star children or personifications of supernatural beings or ancestors (*ibid*).

The physical characteristics of a meteor, such as its brightness and trajectory, have special meaning to the Māori (*ibid*). Bright meteors denote good omens, while fainter ones denote evil omens. If a meteor is seen heading toward the observer, it is a good sign (*ibid*). For example, the matakōkiri are stars that have wandered out of their places and have been struck by their elders – the Sun and Moon. If a matakōkiri appeared to approach a person directly, it was seen as a good omen (*ibid*).

Meteors are sometimes referred to as *Ra ririki* (little shining ones). The twinkling stars are children playing across the robe of Rangi (the sky father). Occasionally one of the children will trip and fall, flashing across the sky in a brilliant light (Reed, 1950, p. 190).

4 Stories of Gods

Meteors are personified as *atua* (supernatural beings; Best, 1955, p. 70). When an atua is expelled from the sky for behaving badly, he is seen as a meteor. Atuas are also known to occasionally visit the Earth (Orbell, 1996, p. 165), suggesting a link between meteors and meteorites.

Rongomai was an atua who provided guidance and protection in war. We know that Rongomai is used to refer to Halley's Comet (Tregear, 1891, p. 425). But Rongomai was also known to move through space and "give off sparks". Best (1955, p. 67) cites an account by Rev. R. Taylor who claimed that when the *Pakakutu pa* (fort) at Otaki was besieged, Rongomai was seen in broad daylight as a "fiery form rushing through space" striking the ground and causing dust to rise. This description clearly illustrates a fireball and subsequent meteorite impact and not a comet. Otaki is approximately 65 km north of Wellington on the western coast of North Island. Best also describes a place named *Te Hapua o Rongomai* at Owhiro Bay, south of Wellington, where an atua is said to have descended to Earth. The illusion of a meteor falling from the sky and impacting in the distance, or closer by, is found across the world however, so this may not actually describe a witnessed event, but may be simply an idea incorporated from folklore.

Tutaka, of the Tuhoe tribe, states that *Tunui* is not a star but a demon – a spirit that flies through space and has a "big head" (Best, 1955, p. 68). Best categorizes Tunui as a comet, but the description clearly indicates that Tunui is a bright meteor or fireball. The appearance of Tunui signals that someone has died. This is also a common perception among Aboriginal groups in northern Australia (Hamacher & Norris, 2010).

In many early writings about astronomical traditions, comets and meteors are often conflated (cf. Hamacher & Norris, 2010). Another story recorded by Best (1955, p. 68) highlights this. He describes Tunui and Te Po-tuatini as spirits that fly through space, which Best identifies as comets. Seen in the night sky, they are the *atua toro* – inquisitive, reconnoitring gods. Their human mediums (usually the tohunga) placate and influence them by means of a ritual saying. Thus, Tunui is employed as a war-god and certain invocations are addressed to him. Comets do not appear to "fly" through space, nor are they fleeting. Instead, they gradually move across the sky from night to night. It is clear that what is described is a meteor and not a comet.

5 Stories of Ancestors & Men

An ancestor and spirit named Tūmatakōkiri is seen as a meteor, according to an "old warlock" of the sons of Awa (Best, 1955, p. 70). Tūmatakōkiri foresees the positions of celestial bodies, and the seasonal and weather conditions, as he flies through the skies (*ibid*). If he moves downward, the following season will be windy. If he maintains a level trajectory, the following season will be successful and bear much fruit.

Hape from Ohiwa is the ancestor of the Te Hapu Oneone people ("the people of the soil", Orbell, 1996, p. 45). He had two sons, Tamarau and Rawaho. Rawaho was the eldest and a tohunga, however, it was Tamarau that entered the house of his father's death first and inherited his father's powers. This turned him into an atua and gave him the power of flight; he would fly around from place to place. Tamarau lived in Kawekawe but if anyone approached his house he would turn into a meteor and fly away.

In Māori astronomical traditions, the bright star Sirius (α Canis Majoris) is called *Rehua* (Stowell, 1911, pp. 201–202). The star is said to have come as a "flaming star from out of the dark-hole", a reference to the Coalsack nebula near the Southern Cross. Rehua flew across the sky with "lighting speed", venturing among the stars before finally settling in his current place in the sky. The motif of a flaming star emerging from the Coalsack is also found in Aboriginal traditions of Australia (Hamacher & Norris, 2010).

6 Stories of Destruction

Māori mythology is rife with connections between fire, the disappearance of the moa (a large flightless bird akin to an ostrich or emu, which is now extinct), and an object falling from the sky (Snow, 1983; Steel & Snow, 1992; Bryant, 2001). Meteors were believed to bring fire to the earth, suggesting a cultural memory of an airburst or meteorite impact event. According to Steel & Snow, the word moa itself is recent; in an early period – called "before the flames" – the Māori called the bird *Pouakai*, but later it was called *Manu Whakatau*. One translation of this is "bird felled by strange fire". The following Māori poem highlights this view (Steel & Snow, 1992, p. 571):

"Very calm and placid have become the raging billows That caused the total destruction of the moa When the horns of the Moon fell from above down."

Steel & Snow (*ibid*) cite a report of a conversation with an 88-year-old Māori chief who claimed that:

"The moa disappeared after the coming of Tamaatea (a man/god) who set fire to the land. The fire was not the same as our fire but embers sent by Rangi (the sky). The signs of the fires are still to be seen where red rocks like berries are found."

Attempts to directly relate these oral traditions to a meteorite impact have been problematic and contentious. In 2003, Dallas Abbott and her colleagues reported the discovery of a putative submarine impact crater 250 km south of Stewart Island (48°.3 S, 166°.4 E) with a diameter of 20 ± 2 km that they believe impacted in 1443 AD (Abbott et al., 2003; Abbott et al., 2005). Abbott and her colleagues named the structure *Mahuika*, after the Māori god of fire, believing this to be the impactor that sparked the Māori traditions described in this section.

Impacts large enough to create a crater 20 km wide are believed to impact the Earth once every three million years (Collins et al., 2005), casting doubt on Abbott's date of 1443 AD. The impact hypothesis relating to the Mahuika structure and the Māori traditions have been challenged (Goff et al., 2003; Goff et al., 2010) but remain a topic of contentious debate (Bryant et al., 2007). An impact origin of the structure is still awaiting confirmation.

7 Discussion

Some of the stories in Māori traditions seem to describe a meteorite fall or impact. Only nine meteorite finds have been confirmed in New Zealand. In order of discovery, they are (from Grady, 2000) Wairarapa Valley (1863: Find), Makarewa (1879: Find), Mokoia (1908: Observed Fall), Morven (1925: Find), View Hill (1953: Find), Waingaromia (1970: Find), Duganville (1976: Find), Kimbolton (1976: Find), and Ellerslie (2004: Observed Fall; Barrett, 2007, p. 25). There is currently no confirmed connection between known meteoritic events and those recorded in Māori traditions. Meteor traditions that may describe an impact from Otaki and Owhiro Bay are in the same general region as the Wairarapa Valley meteorite find in 1863, but any connection between them is speculative. There is no confirmed impact crater associated with the proposed impact event that describes the destruction of the moa. There are no known reports of the Māori using meteoritic material for practical or social purposes. However, these are topics of current research.

8 Conclusion

We have highlighted various views of meteors in Māori stories, religion, and ceremony. The Māori have a broad perception of meteors. We find that they often view meteors as atua (supernatural beings) or ra ririki (children of light). However, meteors are also synonymous with fire and destruction. This is similar to other cultures around the world where meteors are viewed as bad omens (e.g. Hamacher & Norris, 2010). We also find that references to comets and meteors are often conflated, with descriptions of meteors being mistaken for comets.

9 Acknowledgements

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References

Abbott D. H., Biscaye P., Cole-Dai J., and Breger D. (2005). "Evidence from an Ice Core of a Large Impact Circa 1443 A.D. (abstract #pp31c-05)". In *Fall Meeting 2005*. American Geophysical Union.

Abbott D. H., Matzen A., Bryant E. A., and Pekar S. F. (2003). "Did a bolide impact cause catastrophic tsunamis in Australia and New Zealand?". *Geological Society of America Abstracts with Programs*, **35**, 168.

Anderson A. (2009). "Origins, Settlement and Society of Pre-European South Polynesia". In Byrnes G., editor, *The New Oxford History of New Zealand*, Auckland. Oxford University Press, pages 21–46.

Barrett S. (2007). *Why Cooperate?: The Incentive to Supply Global Public Goods.* Oxford University Press, Oxford.

Best E. (1955). *The Astronomical knowledge of the Māori: genuine and empirical.* R. E. Owen, Wellington.

Bryant E. (2001). *Tsunami: The Underrated Hazard.* Cambridge University Press, Cambridge.

Bryant E. A., Walsh G., and Abbott D. H. (2007). "Cosmogenic Mega-Tsunami in the Australia Region: Are They Supported by Aboriginal and Maori Legends?". In Piccardi L. and Masse W. B., editors, *Myth and Geology (Special Publications 273)*, London. Geological Society, pages 203–214.

Collins G. S., Melosh H. J., and Robert A. M. (2005). "Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth". *Meteoritics & Planetary Science*, **40:6**, 817–840.

Evans J. (2009). *Ngā Waka o Neherā – the first voyaging canoes.* Reed Publishing, Auckland.

Goff J., Dominey-Howes D., Chagué-Goff C., and Courtney C. (2010). "Analysis of the Mahuika comet impact tsunami hypothesis". *Marine Geology*, **271**, 292–296.

Goff J., Hulme K., and McFadgen B. (2003). ""Mystic Fires of Tamaatea": Attempts to Creatively Rewrite New Zealand's Cultural and Tectonic Past". *Journal of the Royal Society of New Zealand*, **33:4**, 795–809.

Grady M. M. (2000). *Catalogue of meteorites (5th edition.* Cambridge University Press, Cambridge.

Hamacher D. W. and Norris R. (2010). "Meteors in Australian Aboriginal Dreamings". *WGN, Journal of the IMO*, **38:3**, 87–98.

Harris P., Matamua R., Smith T., Kerr H., and Waaka T. (2013). "A review of Maori astronomy in Aotearoa-New Zealand". *Journal of Astronomical History and Heritage*, **16:3**, 325–336.

King M. (2003). *The Penguin History of New Zealand.* Penguin Books, Auckland.

Kingsley-Smith C. (1967). "Astronomers in puipuis - Maori Star lore". *Southern Stars*, **22**, 5–10.

Mackrell B. (1985). *Halley's Comet Over New Zealand.* Taylor & Francis, Oxford.

Orbell M. (1996). *The Illustrated Encyclopedia of Māori Myth and Legend*. University of New South Wales Press, Sydney.

Orchiston W. (2000). “A Polynesian Astronomical Perspective: The Maori of New Zealand”. In Selin H. and Xiaochun S., editors, *Astronomy Across Cultures: The History of Non-Western Science, Vol. 1*. Springer-Verlag, pages 161–196.

Reed A. W. (1950). *Myths and Legends of Māoriland*. Bradford & Dickens, London.

Snow P. G. (1983). *The Mystic Fires of Tamaatea*. Unpublished manuscript.

Steel D. and Snow P. (1992). “The Tapanui Region of New Zealand: A “Tunguska” of 800 Years Ago?”. In Harris A. W. and Bosell E., editors, *Asteroids, Comets & Meteors 1991*, Houston, Texas. Lunar & Planetary Institute, pages 569–572.

Stowell H. M. (1911). *Maori-English Tutor*. Whitcombe & Tombs, Christchurch.

Tregear E. (1891). *The Maori-Polynesian Comparative Dictionary*. Lyon & Blair, Wellington.

Walter R. and Moeka’a R. (2000). *History and Traditions of Rarotonga by Te Ariki Tara ’Are*. The Polynesian Society, Auckland.

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Fireball with a persistent train on 2013 December 2

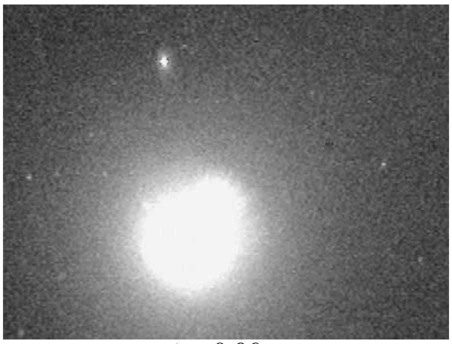
This fireball appeared on 2013 December 2 at $01^{h}31^{m}12^{s}$ UT over Slovenia. Left: All-sky photograph from Črni Vrh Observatory, Slovenia; courtesy of Herman Mikuž. Bottom: Time-series of the fireball, captured from Konstanjevec, Slovenia by METKA camera, using 12-mm $f/0.8$ lens and Mintron camera. Cropped image of every sixth frame is presented during the fireball appearance and every 24^{th} frame for the persistent train. Photo courtesy: Javor Kac.

$t + 0.00$ s

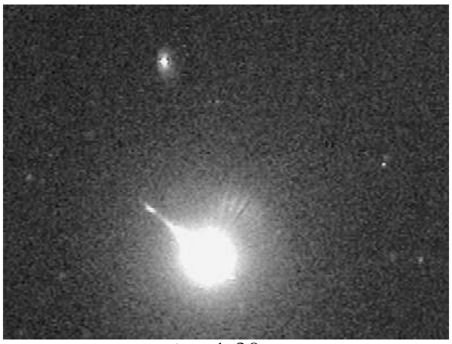
$t + 0.24$ s

$t + 0.48$ s

$t + 0.72$ s



$t + 0.96$ s



$t + 1.20$ s

$t + 1.44$ s

$t + 2.40$ s

$t + 3.36$ s

$t + 4.32$ s

$t + 5.28$ s

$t + 6.24$ s