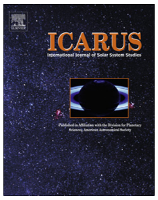
Icarus xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Icarus

journal homepage: www.journals.elsevier.com/icarus



CAMS verification of single-linked high-threshold *D*-criterion detected meteor showers

Peter Jenniskens [a,b,*], Quentin Nénon [a]

[a] *SETI Institute, 189 Bernardo Avenue, Mountain View, CA 94043, USA*
[b] *NASA Ames Research Center, Mail Stop 241-11, Moffett Field, CA 94035, USA*

ARTICLE INFO

Article history:
Received 27 May 2015
Revised 7 October 2015
Accepted 7 October 2015
Available online xxxx

Keywords:
Meteors
Comets, dust
Interplanetary dust
Near-Earth objects
Asteroids

ABSTRACT

From preliminary 2010–2011 results of the *Cameras for Allsky Meteor Surveillance* (CAMS) meteoroid orbit survey, which were combined with published 2007–2009 SonotaCo video meteor network data, 55 new meteor showers (##448–502) were identified and added to the IAU Working List on Meteor Showers in 2012. These showers were identified based on an automated single-linked D_{SH}-criterion analysis of a combined 105,000 orbits with high-threshold (a low $D_{SH} < 0.05$), but low acceptable sample size ($\geqslant 6$ members). Three more years of CAMS and four more years of SonotaCo observations have now increased the meteoroid orbit database four fold. The earlier detections are verified by searching for number density enhancements in drift-corrected radiant and orbital element maps. Twenty showers are detected in both surveys and are now certain to exist. Median orbital elements are presented. Not detected in this manner were 19% of the fast $V_g > 40$ km/s showers, 54% of the $V_g = 18$–40 km/s showers, and 90% of the slow $V_g < 18$ km/s showers.

1. Introduction

An ongoing effort is underway to document the meteor showers on Earth for studies in planetary science, satellite impact hazard mitigation, and planetary defense (Jenniskens, 2006; Williams, 2011; Williams and Jopek, 2014). Each meteor shower is an important record of past comet (or active asteroid) activity, studies of which are only meaningful if the meteor shower is certain to exist. For that reason, the International Astronomical Union maintains a Working List of Meteor Showers to keep track of which streams are known to exist and which require confirmation. New showers are added regularly from ongoing meteoroid orbit surveys (Jenniskens et al., 2009; Jopek and Kanuchová, 2014).

In preliminary work by Rudawska and Jenniskens (2014), we added 55 meteor showers (##448–502) to the IAU Working List on Meteor Showers, based on an automated high threshold single-linking D_{SH}-criterion (Southworth and Hawkins, 1963) analysis of the combined results from two video meteor orbit surveys. The first 40,744 meteors observed during Oct. 2010–Dec. 2011 by our *Cameras for Allsky Meteor Surveillance* (CAMS) video-based meteoroid orbit survey were combined with 64,650 published orbits measured by the *SonotaCo video meteor network* during 2007–2009 (Kanamori, 2009). Orbits were considered similar only when $D_{SH} < 0.05$. This is a strong constraint, given that a relatively weak threshold value of $D_{SH} < 0.25$ is often used (Lindblad, 1971a, 1971b; Kanamori, 2009; Andreic et al., 2013, 2014; Segon et al., 2014a; Gural et al., 2014).

To our surprise, as many as 88 potential showers emerged from this analysis assuming that 6 near identical meteoroid orbits were sufficient for a potential shower to be included in the list (Rudawska and Jenniskens, 2014). 33 were identified as streams already in the Working List, but 55 were likely newly identified showers. In preparation of publication, these showers were reported to the IAU Meteor Data Center. After that, two of these (#462 and #499) were soon recognized to be additional duplicates of showers already in the list and were subsequently removed, leaving 53 showers that need confirmation.

On closer inspection, we found that many of these potential showers were based on only 2–4 meteors detected by CAMS, combined with 2–4 detections by SonotaCo. Individual surveys would not clearly show the streams. After more CAMS observations were available at the end of March 2013, it was confirmed that at least 29 streams could be detected by single-linked D_{SH}-criterion searches in CAMS data alone (Rudawska and Jenniskens, 2014).

---

* Corresponding author at: SETI Institute, 189 Bernardo Avenue, Mountain View, CA 94043, USA. Fax: +1 650 962 9419.
E-mail address: Petrus.M.Jenniskens@nasa.gov (P. Jenniskens).

http://dx.doi.org/10.1016/j.icarus.2015.10.004
0019-1035/© 2015 Elsevier Inc. All rights reserved.

Kornos et al. (2014) reported that 18 of these showers were also detected by automated searches with $D_{SH} < 0.07$ of the meteoroid orbit database EDMOND, based on independent European multi-station video observations, while another 12 showers were more tentatively detected.

It is not certain, however, that single-linked D_{SH}-criterion searches isolate streams of meteoroids from the same parent body, rather than coincidental groupings from a sporadic background. To be certain, evidence of a meteoroid stream should also manifest as a significant number density enhancement over the background (preferably in more than one survey). Now the CAMS database has grown to 238,000 meteoroid orbits and the SonotaCo database has grown to 168,000, we will re-visit these 55 showers here. Previous papers discussed how the established showers (Jenniskens et al., 2015a) and newly confirmed showers (Jenniskens et al., 2015b) manifest in CAMS data.

2. Methods

The SonotaCo video meteor network is a large consortium of amateur astronomers in Japan, who operate about 100 cameras at 25 sites. The results from meteor triangulations using *UfoCapture* software are annually published on the SonotaCo website by Touru Kanamori of Tokyo, Japan. The SonotaCo network has been in operation since 2007, with first results published in 2009 (Kanamori, 2009).

The CAMS network in California consists of 60 low-light video cameras distributed over three stations and was conceived to validate as many as possible of the unconfirmed showers in the IAU Working List of Meteor Showers. The CAMS hardware and custom-made software are described in Jenniskens et al. (2011) and Gural (2012). Each measured meteoroid trajectory defines a radiant, the direction from which the meteoroid is seen to approach us, and an entry speed. The radiant is defined by two angular elements, either geocentric R.A. and Decl. or ecliptic λ and β. In this work, all radiant values are drift-corrected to the solar longitude of the peak of the shower, by correcting for Earth's motion around the Sun, which causes the ecliptic radiant to drift by $\Delta\lambda = 1°$ and $\Delta\beta = 0°$ per degree of solar longitude. The solar longitude is a measure of the position of the Earth in its orbit, proportional to the time of the meteor in a given year. From the time of observation, the radiant direction, and the entry speed, the meteoroid pre-atmospheric orbit is calculated.

Traditional methods to isolate meteoroid streams use one of the so-called discriminant criteria (D), which compare the orbital elements of an orbit to a reference orbit, and exclude those orbits that fall outside a threshold value of similarity (Southworth and Hawkins, 1963; Jopek et al., 2006, 2008). Automatic search routines are used to find groupings of similar orbits in a meteoroid orbit database. The method can also be used in a single-linked manner, where orbits are compared to each other. Each cluster is expanded until there are no further possible orbits within the threshold value of similarity for orbits already in the group.

Alternatively, the number density of radiant and speed values can be statistically analyzed using a hat function if a sufficiently large number of orbits are measured (e.g., Brown et al., 2010). A shower is recognized when a significant excess of number density is observed on consecutive days. Automatic routines are used to link weak threshold crossing events in order to identify showers. This method, too, can lead to spurious detections when too many random threshold crossings are considered. For our video observations, the number of measured orbits is not yet sufficiently large, and the background density in parameter space too variable, for this method to reliably define a suitable threshold in all cases.

Instead, we used the interactive *CAMS Streamfinder* software (Jenniskens et al., 2015a) to search visually in the database for an excess number density of radiants in stacked 10° intervals of solar longitude, then extract that cluster using the D_h-criterion (Jopek, 1993) from the nearby background in two diagrams: the drift-corrected radiant map, and the Π–i diagram showing the orbital elements inclination (i) versus longitude of perihelion (Π). To isolate a corresponding radiant cluster in the Π–i orbital element diagram also demands agreement in entry speed. On the basis of these isolated orbits, median solar longitude, radiant, speed and orbital elements are calculated.

3. Results

Median values of the drift-corrected radiant coordinates, geocentric entry speed, and orbital elements of 24 showers are listed in Table 1. The Tisserand parameter with respect to Jupiter is calculated from the median values of orbital elements from the resulting meteoroid orbit sample. Results are compared to those reported by Kornos et al. (2014) from the independent meteoroid orbit database EDMOND.

Table 2 lists the accuracy of the drift-corrected radiant and speed and their dispersion. The period of activity includes the range of solar longitudes over which shower members were detected (which should be read such that start at 244° and end at 256° means that all detected meteors appeared between solar longitudes 244.0° and 256.0°). The radiant drift is that calculated from the applied drift $\Delta\lambda = 1°$ and $\Delta\beta = 0°$ per degree of solar longitude. Also given is the D_h threshold value used to extract the meteors.

Finding charts for each shower are shown in Figs. 1–22. In each figure, the CAMS data are shown to the left and the SonotaCo data to the right. All data are drift corrected to the solar longitude value listed in column 4 of Table 1, unless stated otherwise.

3.1. Fast showers in the apex and toroidal sources

The individual showers will now be discussed, starting with the long-period comet and Halley-type comet showers from the apex and toroidal sources (Campbell-Brown, 2008), which have a relative high entry velocity $V_g > 40$ km/s.

The June ε-Cygnids (#458, JEC) are a long-period comet type shower (Fig. 1). Shower peak time and orbital elements are in good agreement with Rudawska and Jenniskens (2014). The shower is also detected by SonotaCo and extracted from the EDMOND database (Table 1), confirming that this shower does exist and can be moved to the list of established showers. The parent body is unknown.

The September o-Orionids (#479, SOO) were initially detected from just 18 meteors and are now known to form a structure called the "Orionid Tail" in sun-centered ecliptic radiant coordinates (Fig. 2), which includes the ν-Eridanids (#337, NUE) and early Orionids (#8, ORI). The Orionid Tail was discussed in a previous paper (Jenniskens et al., 2015a). Rudawska and Jenniskens (2014) suggested that Comet P/2005 T4 (SWAN) might be the parent body, but some amount of orbital evolution would be required. The predicted radiant is 23° higher in Right Ascension (Table 1).

The τ-Cancrids (#480, TCA) stand out well in both CAMS and SonotaCo data (Fig. 3). Rudawska and Jenniskens identified this stream from 8 meteors. This shower was also extracted from the independent database EDMOND (Table 1).

The strong January ϕ-Virginids (#500, JPV) are detected well by both CAMS and SonotaCo (Fig. 4). Originally, only 7 meteors were

Please cite this article in press as: Jenniskens, P., Nénon, Q. CAMS verification of single-linked high-threshold *D*-criterion detected meteor showers. Icarus (2015), http://dx.doi.org/10.1016/j.icarus.2015.10.004