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A parent body search across several video meteor data bases

Šegon D.[1], Gural P.[2], Andreić Ž.[3], Skokić I.[4], Korlević K.[5], Vida D.[4], Novoselnik F.[4]

[1]Astronomical Society "Istra" Pula, Park Monte Zaro 2,
52100 Pula, Croatia (damir.segon@pu.htnet.hr)
[2]351 Samantha Drive, Sterling, VA 20164-5539, USA
[3]University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering,
Pierottijeva 6, 10000 Zagreb, Croatia
[4]Astronomical Society "Anonymus", B. Radića 34, 31550 Valpovo, Croatia
[5]Višnjan Science and Education Center, Istarska 5, 51463 Višnjan, Croatia

Abstract. A meteor stream search that uses all the known near-Earth objects (NEOs) as parent bodies, with their individual orbital elements as the starting point, has found statistically significant associations when applied to video meteor data bases. By using the combined CMN–SonotaCo data sets containing 133,652 video meteor orbits, 30 comets were associated with meteor showers of which only 23 were previously listed in the IAU MDC data base. Additionally, 43 asteroids with inclinations over 15 degrees may be associated to streams containing ten or more meteor orbits, each possibly representing a new meteor shower. Lastly, by using a modified search that compared the orbital similarity of each meteor to all other video meteors in the data base, 1093 groupings with more than ten meteors were found that may be indicative of several new minor showers. Of those groups, 6 new showers were found to be potentially associated to a parent body. Several dozen additional groups are planned for publication and submittal to the IAU for their consideration as newly discovered streams. Altogether 56,486 (42%) of the meteors in the combined video meteor data base are in one of the meteor stream groupings found, while the rest are likely sporadics. Further analysis is needed to prove that the groupings found are indeed minor showers.

Keywords: meteor showers, meteoroids, parent body search, video meteor observations

1. Introduction

The ongoing collection of multi-station video meteor orbits through 2013 had reached a point of statistical significance, such that it was time to revisit the search for new minor meteor streams as well as stream associations to potential new parent body candidates. Past searches for new meteor streams within orbital data bases can be found in Lindblad (1971a); Jopek et al. (2003); Svoreň et al. (2000) using photographic orbits, in Sekanina (1976) using radio meteors, and in Greaves (2000) using video derived orbits. In addition, many papers have also been published concerning the connections between meteor streams and either near-Earth asteroids or comets in Drummond (1981); Hasegawa et al. (1992); Jopek et al. (2002); Jopek (2011); Jopek and Williams (2013). Based on these and other previous successes, this work was initiated to re-examine minor meteor streams by utilizing a large combined data base of video meteor orbits. The analysis was started by identifying a "seed" orbit to form the basis of a collection of associated meteors in Keplerian space. The definition of the seed orbit distinguishes the sections of this paper as follows. Section 2 concerns cometary associations to meteor streams using each individual comet's orbital parameters as a seed orbit, section 3 is similar in nature but starting with near-Earth asteroids (NEAs) as the seed orbits for the search, while section 4 involves a twist on past searches in that it treats each individual meteor as a seed orbit to look for associations amongst its neighbors and thereby find new and existing minor streams. Section 5 ends the paper with a brief summary of the findings.

Several data components are utilized in searches of this nature. For the near-Earth objects the latest complete set of orbital elements for both comets and NEAs were downloaded from the JPL small-body data base search engine JPL (2013) which contained 3205 comets and 8824 asteroids. These would provide the seed orbits for parent-body/meteor-stream associations. Clearly a statistically good sample of meteors is beneficial for this type of study, which was in the form of multi-station triangulated video meteor orbits. Since 2007, two independent video meteor camera networks have been monitoring the skies over Japan and Croatia, the SonotaCo Meteor Network and Croatian Meteor Network (CMN) respectively. As a result of five years of collection, their combined catalogues contain over one hundred thirty thousand meteoroid orbits comprised of 114,280 meteors from the SonotaCo data base and 19,372 meteors published by the CMN, spanning the years 2007-2011. References to the data bases can be found in SonotaCo (2009), SonotaCo (2013), Šegon et al. (2012), Korlević et al. (2013), and CMN (2013). Note that the video derived orbits fall between radar and photographic measurement accuracies, with the video's advantage being both a large statistical sample set to work from and possessing good quality Keplerian elements.

The processing approach breaks somewhat from the search methodologies employed in the past, particularly for the individual meteor based seed orbit. Previous studies have often relied on a "single meteor linking technique" dating back to Southworth and Hawkins (1963) and Lindblad (1971a). They begin with a meteor orbit and chain together orbitally similar meteors by treating the pairings independently. This was recognized as potentially suffering from long linked chains where meteors at either end of the chain, can end up being unrelated in their orbital parameters. Thus, tight orbital similarity criteria were applied to minimize this risk. Also in the past, the concept of starting from a single meteor and performing orbital similarity comparisons within a large data base, was considered too computationally burdensome for computer processing systems. This is no longer the case as the total computational time for this study amounted to just a few hours and the entire data base fit easily within modern day computer memory. It is a given that a large portion of the meteors in the analyzed data bases are in fact sporadics, but the authors recognized that a significant fraction of meteors are actually members of a stream and as such, they have neighbors within such a large data base to help form the initial mean orbit of a minor stream. Furthermore a search along the daily drift of the orbital elements in time is included to track the stream across its entire activity period. The assumption is that each and every meteor orbit in the data base could be a potential seed orbit of a minor shower grouping and thus all should be checked for clustering.

A boot-strapping technique was employed that starts with either a single meteor orbit or a near-Earth object orbit as a starting seed. The process first finds meteors with nearly equivalent orbital parameters by applying the usual similarity criteria (described later) and grouping those meteors into a single mean orbit using arithmetic averaging. The new mean orbit is run against the entire meteor data base again and the process is repeated until an unchangeable set of meteors has been found. A converged mean orbital parameter set is calculated along with a mean solar longitude which is close in time to the peak flux.

The second phase takes the newly found mean meteoroid orbit near the time of peak flux, and searches outwards through the data base in solar longitude shifting by one degree wide bins. So for one day ahead, all meteors are D-criteria tested against the converged mean orbit that only fall within the next day's one degree solar longitude bin after the peak. Meteors meeting both the D-criteria and solar longitude bin constraints are averaged, forming a new mean orbit for the day after peak. The search continues by advancing another degree in solar longitude, again finding all meteors meeting the D-criteria constraint relative to the mean orbit of the day before, as well as falling within the one degree solar longitude bin width. This process continues stepping forward in time until the meteor counts in a one degree solar longitude bin falls below two. Then the same process is repeated starting at the time of peak flux and instead working backwards in time, one solar longitude bin at a time. No meteors are mixed in the mean orbits obtained per day since they are segregated by solar longitude bins of one degree width. This approach permits the association of meteors over a long activity profile to a common stream, and thus accounts for changes occurring in a stream's orbital elements over time. The advantage of the technique is that it adds meteors to a group that the similarity criteria may have rejected if only a single mean orbit was used to characterize the stream over its entire activity period.

Three orbital similarity criteria were used in tandem to provide a more robust level of restriction, such that meteors must meet all three thresholds to be grouped together. The classic D-criteria developed by Southworth and Hawkins (1963), and later updated by Drummond (1991) and Jopek (1993), were applied to each independent parent body orbit, meteor orbit, or mean orbit when compared against every available meteor orbit from the video data base, using thresholds of $D_{SH} < 0.15$, $D_D < 0.075$, and $D_H < 0.15$ respectively. These threshold values were selected based on suggestions in papers by various authors such as Lindblad (1971a), Lindblad (1971b), Jenniskens (2006), as well as others. The same threshold levels are used in all the processing, unless stated otherwise.

2. Cometary associations to meteor streams

In the first phase of the study, associations between cometary objects and meteor streams were investigated by starting with a comet as the parent body seed orbit, and candidate meteor orbits were extracted from the video data base by fulfilling the three D-criteria simultaneously. From the resulting list of meteor groupings, when the initial meteor count in a group was higher than ten, the process continued with a search for a possible meteor shower as described previously. For each significant meteor grouping, the resulting orbital parameters, activity period, radiant drift, and other shower characteristics were recorded per degree of solar longitude, and then compared with the orbital parameters of known meteor showers from the IAU MDC database (see Jopek and Jenniskens (2011), Jopek and Kaňuchová (2014)). It is important to note that in some cases, this iterative pro-

Table 1. The list of comets associated to meteor showers as found by the search described in this paper. The number of meteor orbits associated with the particular comet satisfying $D_{SH} < 0.15$ criteria is given in the column "Meteors". Possible new showers found based on this analysis are labeled with a "*". Known showers potentially associated with a parent body are labeled with a "**".

Comet	Meteors	Shower
109P/Swift-Tuttle	5881	Perseids
55P/Tempel-Tuttle	140	Leonids
1P/Halley	998	Orionids,η Aquariids
C/1917F1(Mellish)	327	December Monocerotids
C/1861G1(Thatcher)	281	April Lyrids
8P/Tuttle	202	Ursids
C/1846J1(Brorsen)	110	December σ Virginids
3D/Biela	102	Andromedids
C/1771A1(Greatcomet)	86	July Pegasids
C/1739K1	85	Leonis Minorids
C/1987B1(Nishikawa-Takamizawa-Tago)	85	** ϵ Geminids???
169P/NEAT	74	α Capricornids
C/1979Y1(Bradfield)	74	July Pegasids
C/1911N1(Kiess)	64	Aurigids
45P/Honda-Mrkos-Pajdusakova	56	August δ Capricornids
C/1852K1(Chacornac)	53	η Eridanids
C/1964N1(Ikeya)	46	* July ξ Arietids
C/1983H1(IRAS-Araki-Alcock)	43	η Lyrids
249P/LINEAR	41	not an unique choice
73P/Schwassmann-Wachmann3	38	τ Herculids - not confirmed by this work
255P/Levy	32	* α Cepheids
C/1864N1(Tempel)	31	** δ Piscids
D/1770L1(Lexell)	31	North. μ Sagittariids
185P/Petriew	27	not an unique choice
C/1961T1(Seki)	25	December ρ Virginids?
P/2005JQ5(Catalina)	25	not an unique choice
C/1957U1(Latyshev-Wild-Burnham)	21	* κ Aurigids
21P/Giacobini-Zinner	19	October Draconids - not found in this search
C/1790A1(Herschel)	18	β Aurigids - not confirmed by this work
C/1853G1(Schweizer)	17	* γ Aquilids
C/1943W1(vanGent-Peltier-Daimaca)	17	November Hydrids - not found in this search
197P/LINEAR	16	not an unique choice
C/1862N1(Schmidt)	15	ζ Arietids
C/1975T2(Suzuki-Saigusa-Mori)	15	λ Ursae Majorids
C/2012C2(Bruenjes)	15	* θ Craterids
103P/Hartley2	14	not an unique choice
C/1939H1(Jurlof-Achmarof-Hassel)	14	* θ Cetids
C/1718B1	12	π Hydrids?
C/1870K1(Winnecke)	12	* 51 Andromedids
C/1948L1(Honda-Bernasconi)	12	* 55 Arietids
209P/LINEAR	11	* May λ Draconids
C/1966T1(Rudnicki)	11	—
222P/LINEAR	10	not an unique choice

cess did not produce a well converged and iteratively stable set of meteoroid orbits and therefore the seed comet was excluded as a possible parent body of a meteor shower. However, the search did find the existing known comet-stream associations as well as some new findings. Note there was a final check in the process, to ensure the link between the comet and the single meteors in the resultant meteor grouping were unique. Thus each individual meteoroid orbit in an alleged stream was compared with all known NEOs up through May 1, 2013, to test for orbital similarity to a parent object other than the comet under test.

The complete list of established and possible meteor showers associated with comets found by this search is given in Table 1. As would be expected, the major meteor showers such as the Orionids, Perseids, Leonids and several minor showers were connected to their previously known parent comets. In total, 21 comet parent bodies were reconnected to previously associated meteor streams, which provided evidence that the search method was functioning properly.

In some cases, the D-criteria distance between the "final" mean meteor shower orbit when compared to the cometary "seed" orbit, differed by more than the selected thresholds for D_{SH}, D_D and D_H. But this was likely due to the different dynamical evolution of both the meteoroid stream and the comet's orbit and would require full dynamical modeling of the two, to truly verify the parent-stream associations. Considering the fact that the initial comet's orbital parameters led us to the meteor shower, does suggest that there is some connection between the comet and the meteor stream. Meteor showers with discrepant D-criteria distances between parent and shower (π Hydrids and December ρ Virginids) have been labeled in Table 1 with a question mark after their name to highlight this difference. In addition, those comet cases where single meteors within the associated meteor shower grouping possessed orbital similarities to other NEOs, have been noted in the table as "not an unique choice", meaning that some other NEO may also be the parent body of that particular meteor shower.

Two new possible associations were discovered between cometary parent bodies and minor meteor showers currently listed in the IAU MDC working list, marked by a double asterisk "**" in Table 1. Those are comet C/1987B1(Nishikawa-Takamizawa-Tago) potentially tied to the ϵ Geminid meteor shower, as also found by Olsson-Steel (1987), and C/1864N1(Tempel) potentially connected to the δ Piscids.

More significant are possible links between comets and 9 previously unknown minor meteor showers, noted with a single asterisk "*" in Table 1. The associations cover a wide range of orbits including Jupiter family comets, Halley type comets, very long period comets, as well as comets on parabolic orbits, and span a full range of inclinations. This indicates that the approach does not suffer seriously from selection effects within the realm of cometary association, given the limitation that this is based on meteors sampled strictly at Earth's orbit.

One example of a new shower found by starting the search from a comet's orbital elements is shown in Figure 1, containing plots of the orbits of meteor stream members and radiant connected to comet C/1853G1(Schweizer). Comet Schweizer is a long period comet (approximately 780 year period) having a de-

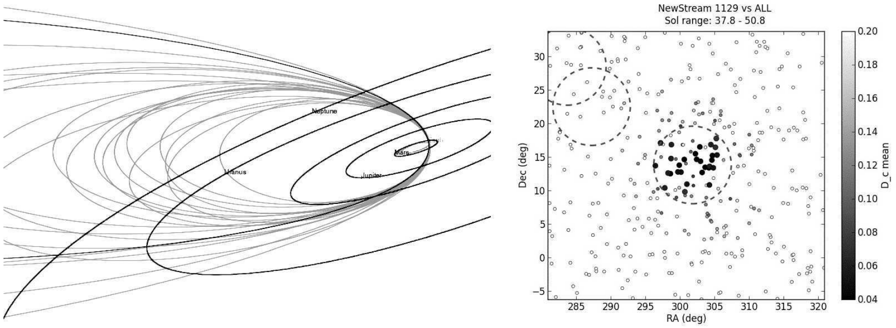


Figure 1. Meteoroid orbit plot (left) for the new stream members associated with comet C/1853G1(Schweizer). The comet's orbit is the black line. The corresponding radiant plot is given on the right side. The difference in D_C to the mean shower orbit is coded with shades of gray where the black end of the scale indicates a high similarity of orbital elements.

scending node distance from Earth's orbit of 0.07 AU, which favors the possibility that we are observing meteors coming from that parent body. Another very interesting discovery are meteors possibly originating from the extremely long period comet C/1939H1(Jurlof- and Achmarof-Hassel) for which were found two associated meteor showers. This comet has nodal crossing distances with respect to Earth's orbit of 0.04 AU and 0.07 AU at the ascending and descending nodes respectively. The two meteor groupings have extremely similar angular orbital parameters, lending credence to our strong opinion that both meteor showers found are really connected to this comet. Due to the small number of meteors found in the search, the second possible meteor shower has not been listed in Table 1.

3. Asteroidal associations to meteor streams

The search for asteroidal connections to meteor streams is more complicated as indicated by previous studies in this arena by Jopek et al. (2002) and others. First, there are many more known NEAs than comets which increase the odds of a chance alignment with a group of meteors. Second, many asteroids have very similar orbits and have been conjectured to be grouped into families, which could effectively span a larger subspace in orbital elements and impose a larger D-criteria threshold (at the moment the existence of families for NEO asteroids is still debated, see for instance Jopek (2011) and Schunová et al. (2011) for both positive and negative opinions). Third, there is an issue of the reliability of the D-criteria used above, due to the existence of large variances in some Keplerian elements arising from low inclination orbit comparisons - a common attribute of NEAs.

Despite these short-comings, this first look at NEA to video meteor stream association was undertaken in the same way as was done for the study of comets above. That is, each NEA is taken as a seed orbit to search for similar orbits amongst the video meteor data base. This resulted in many possible connections when run

Table 2. The list of asteroids with inclination over 15^o associated to meteor showers as found by the search described in this paper. The number of meteor orbits associated with the asteroid is given in the column "Meteors", representing counts for $D_{SH} < 0.15$.

Asteroid	Meteors	Asteroid	Meteors	Asteroid	Meteors	Asteroid	Meteors
3200 Phaethon	8250	2005GE59	31	2004SA	25	2003CQ20	19
2011XA3	213	2002LV	31	2001XU	25	2011GE62	19
2010DG77	53	2011SZ15	30	2013FC8	24	2006TA8	19
2009ST103	47	2009QJ9	30	2013HH19	23	2008GV	19
2000CO33	44	2009VP44	30	2003BK47	23	2010HZ104	18
2001MG1	44	2013EW27	28	2001WH1	22	2001SS287	17
2004UE	42	2008EC69	27	2010TK167	21	2007XN	17
2004CL1	40	2009AD16	26	2010QA5	21	2008TB	17
2007LQ19	36	2005JA45	26	2010UG7	20	2004BE68	15
2010JN71	32	2002JY8	26	2008HK	20	2011FQ17	15
2001XQ	32	2008DD	25	2012KU42	20		

with the same thresholds of D-criteria used previously. In several cases, the low-inclination orbits failed to produce a stable, convergent set of meteors. The D-criteria performance analysis by Galligan (2001), as well as an analysis done by Porubčan et al. (2004) suggests that for inclinations below 10 degrees, a tighter threshold should be used (0.09 and 0.12 per cited paper respectively). Asher et al. (1993) suggests that different D-criteria entirely should be applied for low inclined orbits such as the Northern and Southern Taurid showers, but for the opposite reason, to allow a wider spread in longitude of perihelion. In order to avoid erroneous NEA to meteor stream associations for the similarity criteria thresholds set for this study, the search was limited to asteroids with inclinations higher than 15 degrees. The list of asteroids with the number of associated meteors from the video data base is given in Table 2. As would be expected, the most striking asteroid-to-meteor shower connection is clearly revealed by this search: the asteroid Phaeton and the Geminids meteor stream. Besides Phaeton, our search revealed a possible association between a new meteor shower and asteroid 2001XQ. Since this asteroid lies on an orbit typical for Jupiter family comets, it could be possible that 2001XQ is not an ordinary asteroid, but a dormant comet or extinct comet nucleus.

4. Minor showers found within the video meteor data base

The minor meteor shower search through the video meteor data base was based on the same procedures as used in the NEO search except for two differences. The meaning of the parent body "seed" orbit was modified to represent one of the meteor orbits in the data base rather than an NEO. This essentially states that a single meteor itself is a good starting representative of the mean orbit of a stream, such that given a large data base and comparing every seed meteor to every other meteor, a significant number of similar orbit meteors will combine to form a mean orbit in the first pass through the data (modern computer systems make this level of processing possible on over 130,000 orbits). As before, if the number of meteors satisfying all three D-criteria thresholds was higher than 10, that seed meteor was assigned an associated count and stored in a running list. The process continued evaluating all possible meteors in the data base (each essentially assigned as a seed

Table 3. The list of showers from the IAU MDC list (as of 1st August 2013) found by the second search run. The meteors were claimed to be associated to the particular shower if $D_{SH} < 0.15$, $D_H < 0.15$ and $D_D < 0.075$ are satisfied simultaneously. The number of meteor orbits associated with the particular shower is given in the column "Meteors".

Code	No.	Shower Name	Meteors	Code	No.	Shower Name	Meteors
GEM	4	Geminids	7612	CAN	411	c Andromedids	36
PER	7	Perseids	6289	ACB	429	α Coronae Borealids	35
ORI	8	Orionids	4710	MLE	438	μ Leonids	34
LEO	13	Leonids	1119	SSS	168	Southern σ Sagittariids	33
QUA	10	Quadrantids	996	AMO	246	α Monocerotids	33
NTA	17	North Taurids	895	NAS	483	November α Sextantids	32
HYD	16	σ Hydrids	888	ZCY	40	ζ Cygnids	29
COM	20	Comae Berenicids	814	LUM	524	λ Ursae Majorids	29
STA	2	South Taurids	682	GAQ	531	γ Aquilids	29
ETA	31	η Aquariids	488	NIA	33	North ι Aquariids	28
SDA	5	South δ Aquariids	439	ZAR	193	ζ Arietids	28
FTA	286	ω Taurids	409	OUI	241	October Ursae Minorids	28
CAP	1	α Capricornids	351	TPY	340	θ Pyxidids	28
MON	19	December Monocerotids	319	NSA	67	North μ Sagittariids	27
SPE	208	September ϵ Perseids	280	CTA	388	χ Taurids	27
LYR	6	April Lyrids	270	THA	390	November θ Aurigids	27
URS	15	Ursids	258	AUP	415	August Piscids	27
KCG	12	κ Cygnids	232	FPL	501	February π Leonids	27
NOO	250	November Orionids	226	XHE	346	x Herculids	26
JCO	90	January Comae Berenicids	156	BAR	434	β Arietids	26
ORN	256	North χ Orionids	146	GBO	104	γ Bootids	25
EGE	23	ϵ Geminids	142	BCN	232	Dayt. β Cancrids	25
ZCS	444	ζ Cassiopeiids	135	GUM	404	γ Ursae Minorids	25
AND	18	Andromedids	132	FMV	516	February μ Virginids	25
ERI	191	η Eridanids	120	UUM	527	υ Ursae Majorids	25
DSV	428	December σ Virginids	113	UAN	507	υ Andromedids	24
EHY	529	η Hydrids	113	FLY	511	15 Lyncids	24
DKD	336	December κ Draconids	112	FOA	534	51 Andromedids	24
XVI	335	December χ Virginids	104	BAQ	519	β Aquariids	22
BCD	268	β Cancrids	101	DAB	497	December α Bootids	21
JPG	462	July γ Pegasids	92	DSE	34	δ Serpentids	20
LMI	22	Leonis Minorids	89	PDF	45	ϕ Draconids	20
NUE	337	ν Eridanids	89	OCT	281	October Camelopardalids	18
OER	338	o Eridanids	78	AIC	505	August ι Cetids	18
AHY	331	α Hydrids	75	OLE	515	o Leonids	18
HVI	343	h Virginids	75	ALO	517	April λ Ophiuchids	18
PPS	372	ϕ Piscids	73	FHE	345	f Herculids	17
NDA	26	North δ Aquariids	70	MPR	435	μ Perseids	17
DAD	334	December α Draconids	70	AED	450	April ϵ Delphinids	17
POR	430	September π Orionids	66	XCB	323	ξ Coronae Borealids	16
KUM	445	κ Ursae Majorids	65	ARC	348	April ρ Cygnids	16
DRV	502	December ρ Virginids	65	CVN	403	Canum Venaticids	16
ECV	530	η Corvids	64	JIP	431	June ι Pegasids	16
AUR	206	Aurigids	63	JEC	458	June ϵ Cygnids	16
NPI	215	North δ Piscids	63	DEL	494	December Lyncid	16
PSU	339	ψ Ursae Majorids	63	JLE	319	January Leonids	15
DXL	204	Dayt χ Leonids	61	THC	535	θ Cetids	15
DLI	47	μ Virginids	55	TAH	61	τ Herculids	14
GDR	184	July γ Draconids	53	KSE	27	κ Serpentids	13
JRH	463	July ρ Herculids	52	XLI	140	April χ Librids	13
TCA	480	τ Cancrids	52	MIC	370	Microscopiids	13
ELY	145	η Lyrids	50	RPU	512	ρ Puppids	13
JBO	170	June Bootids	49	UCE	194	υ Cetids	12
SLY	81	September Lyncids	48	SCA	179	σ Capricornids	11
BAU	210	β Aurigids	48	SPI	216	South δ Piscids	11
DPI	410	δ Piscids	47	OMO	227	October Monocerotids	11
DMH	498	December μ Hydrids	47	GCM	395	γ Canis Majorids	11

Table 3. Continuation

Code No.	Shower Name	Meteors	Code	No.	Shower Name	Meteors
ICY 525	ι Cygnids	46	NBO	432	ν Bootids	11
NHY 121	ν Hydrids	45	NZT	485	November ζ Taurids	11
KAU 537	κ Aurigids	45	MBC	520	May β Capricornids	11
PIH 101	π Hydrids	44	DSX	221	Dayt. Sexantids	10
DCL 443	December Leonids	44	AAL	448	April α Librids	10
AGC 523	August γ Cepheids	44	FFA	538	55 Arietids	10
ASC 55	α Scorpiids	43	AAN	110	α Antliids	9
OCU 333	October Ursae Majorids	41	SSA	237	σ Arietids	9
XUM 341	January ξ Ursae Majorids	38	DCM	398	December Canis Majorids	9
NLY 437	November Lyncids	38	JMC	362	June μ Cassiopeiids	8
AXC 465	August ξ Cassiopeiids	38	AHE	518	April 102 Herculids	7

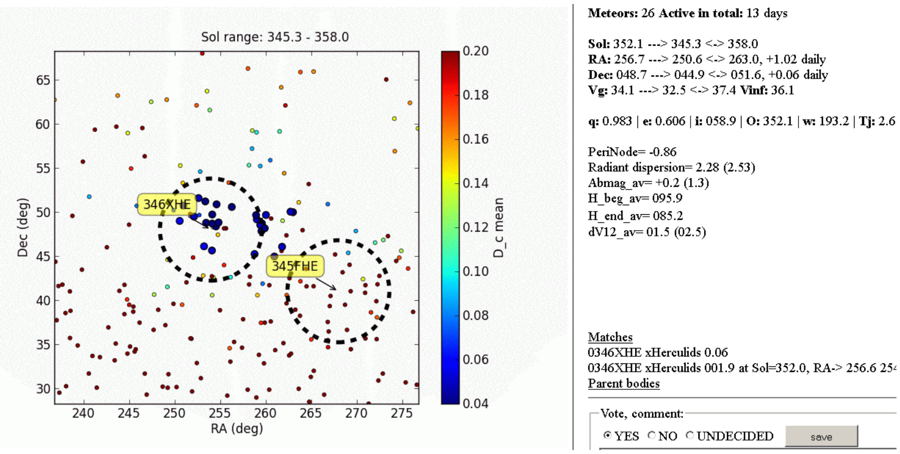
orbit). This first pass produced a very long list of possible meteor groupings (they are not referred to as potential showers in this stage of analysis), having in all 56,486 meteors out of the 133,652 meteor orbits available, which were assigned into one of 3,172 groups.

The second pass through the data base attempted to avoid contamination of minor streams by major showers and is the other modification to the process. In count sorted order from highest to lowest, each running list meteor orbit was again assigned as a seed orbit, and the more extensive processing discussed in the introduction was applied to estimate the daily mean orbital estimates across the stream's activity period. Thus sweeping up all meteors associated with a particular shower. These were then removed from the pool of available meteor orbits before the next lowest count meteor orbit on the running list was set up as the new seed orbit. The process continued until all meteor seeds with significant counts had been processed. The remaining meteors in the pool effectively make up the sporadic meteor population.

After the second pass, the mean orbital parameters for some groups were found to be very similar to other groupings, so each group's mean orbital values were compared to all the other groups. These similarities were likely due to the poorly estimated orbital parameters of single meteors falling just outside the D-criteria of a given group. If a test group contained a smaller number of meteors than a reference group, and also had mean orbital parameters fulfilling a somewhat relaxed D-criterion relative to the reference group, that test group was excluded from further analysis. The similarity threshold was set to the slightly higher values of $D_{SH} < 0.20$, $D_D < 0.10$ and $D_H < 0.20$ to perform this culling. These thresholds were selected to ensure that potentially close but distinct groups of orbits, remain on the list for further analysis. However, this process did cull the number of groups significantly, leaving a total of 1,093.

To verify if this processing yielded valid streams, we compared the results with the data for existing meteor showers already listed in the IAU MDC database. The potential matching was done in one of two ways. The first was by means of an orbital similarity test for cases where the orbital parameters were also available for showers in the MDC. For each group found in the video data base search, the D_{SH}, D_D and D_H values were calculated against all the meteor showers in the MDC list and reported when $D_{SH} < 0.15$, $D_D < 0.075$ and $D_H < 0.15$. The second matching method was applied in cases where the mean orbital parameters were not available from the IAU MDC, where the MDC only contained the right ascension (RA), declination (DEC) and solar longitude at the time of maximum activity. In those cases, the radiant drift values were obtained for each group from the video meteor analysis, and the radiant's RA and DEC values were calculated for the solar longitude of maximal activity given in the IAU MDC for a specific shower. If the resulting radiant separation was smaller than 5 degrees, the radiant distance as well as the shower IAU code name, were reported along with the group analyzed. Moreover, in order to ensure that some meteor groups found in this way were truly representative of a meteor shower, an interactive tool was developed to present various orbital element plots to an analyst, containing details on a variety of orbital parameter pairings to better visualize the association of meteors in each group's dataset.

If the orbital parameters for a given group matched a known meteor shower from the IAU MDC data base by one of the two methods above, and in addition passed the visual inspection for neighboring showers in the Keplerian subspace via the visualization tool, the group was declared to have been matched to a particular meteor shower. An example of such a group to known meteor stream matching is shown in Figure 2.



Meteors: 26 **Active in total:** 13 days

Sol: 352.1 ---> 345.3 <-> 358.0
RA: 256.7 ---> 250.6 <-> 263.0, +1.02 daily
Dec: 048.7 ---> 044.9 <-> 051.6, +0.06 daily
Vg: 34.1 ---> 32.5 <-> 37.4 **Vinf:** 36.1

q: 0.983 | **e:** 0.606 | **i:** 058.9 | **O:** 352.1 | **w:** 193.2 | **Tj:** 2.6

PeriNode= -0.86
Radiant dispersion= 2.28 (2.53)
Abmag_av= +0.2 (1.3)
H_beg_av= 095.9
H_end_av= 085.2
dV12_av= 01.5 (02.5)

Matches
0346XHE xHerculids 0.06
0346XHE xHerculids 001.9 at Sol=352.0, RA-> 256.6 25
Parent bodies

Vote, comment:
● YES ○ NO ○ UNDECIDED save

Figure 2. An example of one product from the data visualization tool used in the detailed group to shower matching. Existing shower radiants from the MDC are shown in dashed black circles while individual meteor orbit D-criteria distances are plotted as colored dots. Larger dots are for the grouped meteors alleged to be in a common stream.

The list of showers in the IAU MDC database (as extracted on August 1, 2013) that were also found by this search method is given in Table 3. For the 93 established meteor showers, this search confirmed the existence of 54 of them. Regarding the rest, in 6 cases the radiant lies below minus 30 degrees declination (thus making them very hard to detect in the northern hemisphere based CMN and SonotaCo data bases), 27 are daytime meteor showers, and the remaining 6 showers (South.

ι Aquariids, October Draconids, η Virginids, October Capricornids, α Lyncids and the February η Draconids) were not detected. The latter case is most likely due to their variable (and very low) activity level. Further details of the results from this search will be published in the near future and will include several dozen newly discovered streams. Stream parameters on a number of the most prominent new minor showers detected has already been sent to the IAU MDC and placed on their list of meteor showers awaiting validation as an established shower. A separate web page is being hosted by the CMN containing all the detailed plots and search results and will be made available to the public in the near future.

5. Conclusions

The current analysis has resulted in the confirmation of existing relationships between known meteor showers and parent bodies, as well as several new associations of statistical significance that are in need of further study. The search methodology employed of using a parent body ”seed” orbit to identify potential meteors on similar orbits through the use of a large meteor orbit data base, is highly effective for verifying existing parent-body to meteor shower associations as well as quantifying the duration and Keplerian element temporal behavior of meteor streams. This search resulted in findings of new possible meteor shower to parent body connections which were not known previously. The reasons why the new associations between comets and meteor showers may not have been found during previous searches (e.g. Drummond (1981)) is likely due to the different types of data samples searched, the size of the meteor orbit data bases, or searches based on less accurate orbits obtained from radar observations.

An important point to emphasize is that all these new findings need to be checked via dynamical modeling of hypothetical meteor streams produced by any connected parent body to validate they are truly associated to the actual streams found. In addition, this work can be extended to include the growing number of meteor orbit databases, which will also help to validate the results of this search.

Finally, we found a large number of very low flux meteor showers potentially associated with both asteroids and comets, where additional sample support is needed for confirmation. We hope that in the near future with further multi-station meteor orbit data base growth and the publication of the CAMS system data by Jenniskens et al. (2011), which contains higher accuracy meteor orbits dating back to November 2010, the additional candidate associations can be verified.

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References

Asher D.J. et al., 1993, MNRAS 264, 93

CMN download page, 2013, `http://cmn.rgn.hr/downloads/downloads.html`

Drummond J.D., 1981, Icarus 45, 545

Drummond J.D., 1991, Icarus 89, 14

Galligan D.P., 2001, MNRAS 327, 623

Greaves J., 2000, Radiant 22, 27

Hasegawa I. et al., 1992, PASJ 44, 45

Jenniskens P., 2006, Meteor Showers and their parent comets, Cambridge University Press

Jenniskens P. et al., 2011, Icarus 216, 40

Jopek, T.J., 1993, Icarus, 106, 603

Jopek, T.J., Valsecchi G.B., Froeschle Cl. , 2002, Asteroids III, Univ. of Arizona Press, Tuscon, 645

Jopek, T.J., Valsecchi G.B., Froeschle Cl., 2003, MNRAS 344, 665

Jopek T.J., Jenniskens P., 2011, Proc. Meteoroids Conf., held in Breckenridge, Colorado USA, May 24-28, 2010, 7

Jopek T.J., 2011, EPSC-DPS Joint Meeting 2011, 15

Jopek T.J., Williams I.P., 2013, MNRAS 430, 2377

Jopek T.J., Kaňuchová Z., 2014, Proc. Meteoroids Conf., held in Poznań, Poland, Aug. 26-30, 2013, eds Jopek T.J., Rietmeijer F.J.M., Watanabe J., Williams I.P, AM University Press, Poznań, p. 353

JPL, 2013, http://ssd.jpl.nasa.gov/sbdb_query.cgi

Korlević K. et al., 2013, WGN 41:2, 48

Lindblad B.A., 1971a, Smithson. Contrib. Astrophys., No. 12, 14

Lindblad B.A., 1971b, Smithson. Contrib. Astrophys., No. 12, 1

Olsson-Steel D., 1987, MNRAS 228, 23p

Porubčan V. et al., 2004, EM&P 95, 697

Schunová E., 2011, EPSC-DPS Joint Meeting 2011, 1875

Sekanina Z., 1976, Icarus 27, 265

SonotaCo, 2009, WGN 37:2, 55

SonotaCo, 2013, `http://sonotaco.jp/doc/SNM/index.html`

Southworth R.B., Hawkins G.S., 1963, Smith. Cont. Aph. 7, 261

Svoreň et al., 2000, Planetary and Space Science 48, 933

Šegon D. et al., 2012, WGN 40:3, 94