Constraining the Physical Properties of Meteor Stream Particles by Light Curve Shapes Using the Virtual Meteor Observatory

D. Koschny • M. Gritsevich • G. Barentsen

Abstract Different authors have produced models for the physical properties of meteoroids based on the shape of a meteor's light curve, typically from short observing campaigns. We here analyze the height profiles and light curves of ~200 double-station meteors from the Leonids and Perseids using data from the Virtual Meteor Observatory, to demonstrate that with this web-based meteor database it is possible to analyze very large datasets from different authors in a consistent way. We compute the average heights for begin point, maximum luminosity, and end heights for Perseids and Leonids. We also compute the skew of the light curve, usually called the *F*-parameter. The results compare well with other author's data. We display the average light curve in a novel way to assess the light curve shape in addition to using the *F*-parameter. While the Perseids show a peaked light curve, the average Leonid light curve has a more flat peak. This indicates that the particle distribution of Leonid meteors can be described by a Gaussian distribution; the Perseids can be described with a power law. The skew for Leonids is smaller than for Perseids, indicating that the Leonids are more fragile than the Perseids.

Keywords meteor light curves · physical properties · meteoroids · double-station observations

1 Introduction

The shape of the light curve of meteors can be used as an indicator for the physical properties of the underlying meteoroid particle. In general, a single solid grain would be expected to increase in brightness and stop emitting light at the end of its flight path at the point of maximum brightness. Fragile particles will start to disintegrate high up in the atmosphere, and the luminosity will be the sum of the light emitted around the individual particles. In the extreme case, a meteoroid will fragment very quickly and reach its highest magnitude early on in its light curve. As the individual particles ablate and slow down, the magnitude of the complete meteor will decrease slowly over its path.

Several authors have analyzed larger numbers of observational data, typically from observing campaigns of meteor streams (*e.g.* Fleming *et al.* 1993, Murray *et al.* 2000, Koten *et al.* 2004). Data from very few meteors was analyzed in very high detail *e.g.* by Jiang and Hu (2001) or Campbell-Brown and Koschny (2004). All of these analyses derive meteoroid physical properties from the shape of the

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light curves. The underlying model is based on an idea by Öpik (1958) and was worked out in detail by Hawkes and Jones (1975) into the so-called dustball model. It assumes that meteoroids are composed of small grains held together by a low boiling point 'glue'. By heating up the meteoroid this glue is evaporated and the particles disintegrate. This model was detailed *e.g.* by Beech and Hargrove (2004). Koschny *et al.* (2002) have modeled the light curve of meteors based on assuming mechanical fragmentation; Campbell-Brown and Koschny (2004) use a detailed aerodynamical model adding a thermal fragmentation mechanism. In this paper we analyze data obtained in several meteor campaigns, but also one data set (from the Perseids 2009) found only by data mining within the Virtual Meteor Observatory (VMO). In addition to the light curve evaluation, one goal of this work was to assess the useability of the VMO for this task.

2 Input Data and Observational Setup

We have been using data stored in the openly available Virtual Meteor Observatory. The Virtual Meteor Observatory (VMO) is a data storage facility for a wide range of meteor data; see Koschny *et al.* (2008) and Barentsen *et al.* (2008a, 2008b). In the currently available beta version single station video meteor data of the International Meteor Organization until ~2007 has been ingested. In addition, double-station data of selected campaigns in the time span from 1997 to 2009 is available. The database can be queried remotely using SQL syntax (SQL = Structured Query Language). All queries used for the paper here are available and can be reused in exactly the same way once more data is available.

In this work we use so-called orbit data sets of the VMO. Most of them are derived from dedicated double-station observing campaigns, using image-intensified camera systems. One of the datasets was extracted by using the VMO functionality of finding potential double-station meteors. This query will go through the existing single-station data for a given time range, and read out the location and pointing direction of all cameras in the database. From the derived geometry, it will identify camera systems which look into the same volume in the atmosphere. Given a maximum delta time, the VMO will identify all observations which could possibly be the same meteor. A list of potential double-station meteors is then presented to the user. The user can select which one (or all) of the meteors should be used for computing orbits. The orbit computation is also done within the VMO using the software MOTS (Meteor Orbit and Trajectory Software, Koschny and Diaz del Rio, 2002).

The contents of such a data set is a list of orbits computed from the observations from two different stations, giving time and initial shower association of a meteor together with all the orbital elements and their associated error bars. Additionally computed information is the peak magnitude of the meteor, a derived photometric mass, velocities, height for the begin, peak brightness and end points, the apparent and geocentric radiant of the meteor, the zenith angle and convergence angle, and a flag whether the meteor started and ended in- our outside the field of view.

The cameras used to produce the data sets were either image-intensified cameras as described in Koschny *et al.* (2002) with field of views between 20° and 60° or, in the case of the Perseids 2009, a non-intensified Mintron camera with a 6 mm f/0.8 wide-angle lens yielding a field of view of 60°. The typical stellar limiting magnitude of the intensified cameras was between 5 and 6 mag; for the non-intensified camera of the Perseids 2009 data the limiting stellar magnitude was around 3 mag.

The following datasets were used:

(a) Perseids 1997 (data set name ORB-KOSDE-PER1997), using two intensified video cameras with 30 deg circular field of view, a faintest star of 6.5 mag, and using a total of 74 meteors;

(b) Perseids 2007 (data set name ORB-KOSDE-PER2007), again using intensified video cameras with 30 deg circular field of view, a faintest stellar magnitude of 6.5 mag, using a total 28 meteors;
(c) Perseids 2009 (ORB-KOSDE-PER2009), using one intensified video camera, one un-intensified camera, with only 13 orbits available.
(d) Leonids 2001 (ORB-BARGE-LEO2001), using two intensified video cameras with 15 x 12 and 33 deg field of view, with 64 available orbits.

From these datasets, we selected only meteors containing 8 or more magnitude datapoints.

3 Results

3.1 Height Distribution

For each dataset, we determined the average beginning height, height of peak light intensity, and average end height. The errors were computed by simply taking the standard deviation of the individual data points. To interpret these errors, one should keep in mind that the input data is quantized. Assume one meteor has precisely 8 data points, and it starts at 110 km and ends at 95 km (for a typical Perseid, see Figure 1). Then the 'quantization noise' already is about 15/8 km ~ 2 km. So each individual meteor height can not be determined more accurate than this simply due to the fact that we look at discrete video images. Table 1 shows the results.

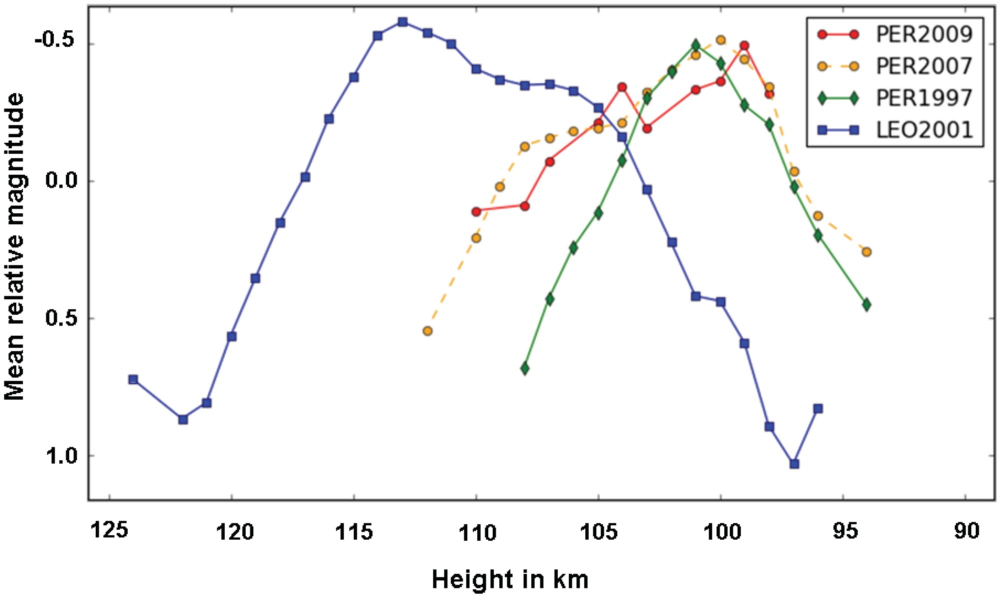

Figure 1. Average light curves from two different meteor showers. For a detailed explanation, see the text. No error bars are shown at the data points; the typical deviation between the mean value and the actual magnitude of a meteor in the given height bin is about 0.3 mag (indicated in the upper left area).

Table 1. Average heights for the beginning point, the point of peak brightness, and the end point for the different datasets. For comparison, the values from a very similar paper as this one (Koten 2004) are given in the same table. The last column lists the *F*-parameter which indicates the skew of the light curve.

Dataset	h_{begin} in km	h_{peak} in km	h_{end} in km	*F*
This work:				
PER1997	107.7 +/- 3.1	100.6 +/- 3.2	96.0 +/- 3.5	0.61 +/- 0.19
PER2007	113.8 +/- 3.7	102.4 +/- 3.7	97.5 +/- 2.9	0.68 +/- 0.21
PER2009	115.1 +/- 12.1	97.8 +/- 7.2	93.1 +/- 8.1	0.75 +/- 0.20
LEO2001	117.0 +/- 10.9	110.1 +/- 10.3	103.0 +/- 10.7	0.47 +/- 0.26
Koten 2004:				
PER1998-2001	113.9 +/- 2.4	104.4 +/- 2.9	96.0 +/- 4.1	0.535 +/- 0.010
LEO2000	120.0 +/- 3.5	106.9 +/- 3.8	96.5 +/- 3.7	0.498 +/- 0.014

3.2 Light Curves and *F*-parameter

We present a novel way to show the typical light curves of a meteor stream. For each individual meteor, we compute the average brightness in magnitudes. Each individual brightness measurement is converted to a relative brightness by subtracting the average value. We then take height bins of one kilometer and average all values in this bin. This results in a smooth curve which is an indication for the typical light curve behavior of a meteor stream, independent of the magnitude.

All Perseid years showed meteors starting between 108 and 113 km, ending between 94 and 97 km. The peak seems to shift slightly from ~102 km in 1997 to 97-99 km in 2007/2009. However, due to the small number of meteors analyzed one should be careful in giving this result too much significance. The important result is that all three years the light curve is clearly peaked, with the peak slightly behind the half length of the profile.

The Leonids begin much higher, the end height is close to the Perseid end height. The main difference to the Perseids is that the curve shows a flat-topped shape, i.e. between 115 km and 105 km the brightness as about constant. This can mean that either all meteors are really flat-topped, or that the peak height of the Leonids varies in this range in such a way that the average curve looks flat. Looking at several individual light curves the former seems to be the case. This is also consistent with Murray (2000) for their Leonids 1998 data but not for their 1999 data.

Note that by displaying the curve like this, any relation between e.g. end height and brightness will be hidden. The apparent increase in magnitude at the begin and end point are assumed to be artifacts, possibly by contamination due to sporadic meteors.

The *F*-parameter (Hawkes and Jones, 1975, Fleming 1993) is defined as

$$F = \frac{H_{begin} - H_{\max}}{H_{begin} - H_{end}}$$

where H_{begin} is the beginning height, H_{max} the height of peak brightness, and H_{end} the end height. The *F*-parameter was computed for each meteor individually. The result is shown in Figure 2 as a function of absolute magnitude (the peak magnitude normalized to a distance of 100 km) and shower. Obviously, the *F*-parameter is ill-defined for a flat-topped meteor light curve. Thus, interpreting of the Leonid results has to be done with care. Still, it can be seen that the values for the Leonids are in a different regime than those for the Perseids. For a given absolute magnitude, the Leonids show lower *F*-

parameters, i.e. the peak occurs earlier. In the average light curves shown in Figure 1 this is evident by the bump in the light curve for high altitudes; Table 1 shows the average *F*-parameter which is 0.47 for the Leonids but between 0.6 and 0.75 for the Perseids.

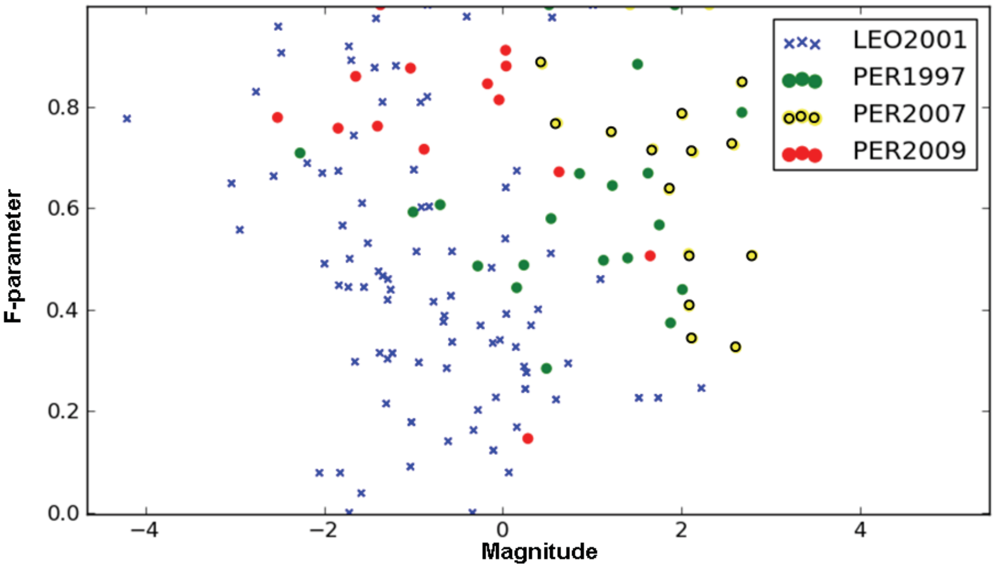

Figure 2. The *F*-parameter as a function of absolute magnitude for the different data sets. A value of 1 means that the meteor has its peak brightness at the end; 0.5 indicates that the light curve is symmetric. Average values are shown in Table 1, this Figure shows the trend between different meteor streams and the relation to the magnitude.

Both Leonids and Perseids show an 'empty region' in the lower left part of the diagram with the same tendency – there are no low *F*-values for brighter meteor, i.e. the brighter the meteor, the later it reaches its maximum.

3.3 Discussion

Beginning, peak, and end heights as reported here are in good agreement with other papers; for comparison we give the height data and the *F*-parameter as determined by Koten *et al.* (2004) in Table 1. The beginning height is an indication for the fragility of the meteoroids. More fragile meteoroids will disintegrate at larger heights, increasing in brightness above the detection level (Koten *et al.* 2004). We can thus confirm that the Leonids are more fragile than the Perseids. This is confirmed by comparing the *F*-parameter: The Leonids on average peak earlier than the Perseids (Note, however, that the flat-topped shape of the average light curve of the Leonids makes it more difficult to define the *F*-parameter).

Plotting the *F*-parameter as a function of magnitude shows that brighter meteors normally peak later. This has been shown for the Leonid 2001 dataset before by a different data interpretation method (Koschny *et al.* 2002) and can be explained by assuming that a single large grain which is not disintegrating is part of the meteoroid. The observed 'empty' region in the lower left area of Figure 2 can be interpreted such that brighter meteors always must contain one or several large grains, which do not disintegrate easily. This shifts the peak of the light cuve to the back.

Current meteoroid ablation models typically assume that meteoroids disintegrate when entering the Earth's atmosphere. The individual fragments ablate and generate light. The shape of the light curve depends on the size distribution of these fragments. Campbell-Brown and Koschny (2004) use *e.g.* Gaussian and power-law distributions to fit different light curves. Typically the Gaussian distribution will better fit the flat-topped light curve; power laws will better fit peaked light curves. Alternatively one can use a Poisson distribution derived from fracture mechanics to describe both shapes (Koschny *et al.* 2002) which is proposed here as it would allow to use only one number (the Poisson coefficient) to describe all light curve shapes.

Flat-topped light curves have been observed before for the Leonids, see Murray *et al.* (2000). They only see the flat-topped light curves for their 1998 data; the 1999 data is more consistent with a peaked light curve. They argue that the 1998 has been ejected from the comet several revolutions before the material encountered in 1999. The longer flight time could imply that the meteoroids had been more fragmented over time. Our observation of flat-topped light curves for the 2001 Leonids is consistent with that proposal - most of the particles recorded by us in Australia are expected to be from the 1699 perihelion (Asher 2000).

4 Conclusion

We have used the Virtual Meteor Observatory (VMO) to retrieve data of double-station observations of the Leonids 2001 and the Perseids 1997, 2007, and 2009. The 2009 data camera from cameras initially operated as single stations; the VMO functionality was used to identify the used camera systems as providing data of the same meteors.

We analyzed the height profiles and light curves of all meteors having more than 8 data points (typically this means having more than 8 video frames). Our height data is consistent with other author's results. The peak of the light curves of our Perseid meteors is somewhat later than in other publications, but showing the same trend.

From the shape of the average light curves we can confirm that the Leonids are more fragile than the Perseid meteors. The Leonids show a more flat-topped light curve. Murray et al. (2000) explain flat-topped versus peaked light curves by assuming a much higher meteor stream age. Our measurements confirm this proposal.

In addition to the scientific results, we conclude that the concept of the VMO is good and the VMO can be used for doing extensive data mining once it has been moved from its current beta-version state to the final version. Additional data on meteors which would go beyond the scope of this paper is easily available and can be retrieved with a simple SQL query, *e.g.* plotting the end height versus photometric mass can be done in one line. However, the current data quality for orbital data still has to be improved. It is recommended that the VMO implement clearly defined data quality criteria. An important additional routine which would be needed in the VMO to allow further studies in the direction shown here would be to add an automated stream association mechanism. Currently, the meteor streams are simply assigned the shower code given by MetRec to the single-station data, which turned out to be not always correct after manually checking the orbital elements.

The VMO will contain single-station data from the IMO video camera network and dedicated double-station data. Discussions are ongoing to include the SonotaCo network (SonotaCo et al. 2010) data. This will make the VMO the largest database for meteor data so far. While the data used here is not yet more numerous than previous studies, all these large datasets will be accessible using exactly the same scripts once the archive is fully operational.

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