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Key Points:

- Short-time (one to few days) elevations of the median and quartiles of the meteor trail height distribution are observed by the Sodankylä meteor radar
- Meteoroids belonging to the showers produce ionization trails at altitudes noticeably exceeding those of sporadic background
- The effect is due to different properties of the sporadic meteoroids and shower members

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Recognition of Meteor Showers From the Heights of Ionization Trails

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Abstract Meteoroids constantly enter the Earth's atmosphere, collide with atmospheric molecules, and heat and ablate in the sufficiently dense atmospheric layers at heights between 70 and 110 km. It is still a problem to recognize properties of the meteor streams among the sporadic background. The meteor radar observations at Sodankylä Geophysical Observatory (67°22'N, 26°38'E, Finland) during 2008–2017 show that meteoroids of some showers produce ionization trails at altitudes noticeably exceeding those of sporadic meteors. Using the median height of meteor trails and corresponding upper and lower quartiles as a metric, we unambiguously distinguish all northern hemisphere meteor showers with a zenithal hourly rate larger than 12, namely, the Quadrantids, Lyrids, Eta Aquariids, Arietids (or/and Daytime Zeta Perseids), Perseids, Orionids, Leonids, and Geminids. Additionally, signatures of a possible meteor stream during 26–30 January were detected, although identification of this stream is still under question. This new analysis indicates that the origin of the shower meteor trails at higher altitudes is likely due to higher speed and probably lighter or less dense meteoroids belonging to the showers.

Plain Language Summary Sporadic meteors and shower meteors originate from different extraterrestrial bodies and thus have specific properties (composition, size, velocity, and angle at which they enter the atmosphere). Meteor radar is able to detect the meteor showers because the meteors belonging to a particular shower ablate at different altitudes.

1. Introduction

The main sources of cosmic dust are collisions between asteroids, the thermal decomposition of surface minerals, and the sublimation of dust-laden icy comets as they approach the Sun on their orbits through the solar system. Dust particles from the asteroid belt and long-decayed comet trails give rise to sporadic meteors, while dust trails produced by the comets which crossed the Earth's orbit relatively recently are considered as sources of meteor showers or streams. Meteor showers are known as periods of unusually high rate of optical meteors coming from the same radiant. Some of the showers, being caused by annual meteor streams, repeat each year, while irregular, nonrepeating showers also exist. A tight group of meteoroids that actually do not originate from the same parent body may be optically detected as a shower (Jenniskens, 2006). There remains a problem to recognize properties of the meteor streams among the sporadic meteor background.

The recognition of the streams is important at least in three aspects. First, it is meteor streams that pose a danger for satellites in the orbit. Second, meteor showers help to identify the comet matter and to distinguish it among the population of asteroids. Finally, the characteristics of the streams may serve as early warning of comet impacts. The approach of a comet to the Earth has potential dramatic destructive consequences (Lewis, 2000). Our ability to identify any systematic changes in the behavior of extraterrestrial bodies well in advance is crucial to find the best solution to such a possibility.

Several thousand meteoroids enter Earth's atmosphere each day, collide with atmospheric molecules, heat, ablate, and produce ionization in the sufficiently dense atmospheric layers at heights mostly between 70 and 110 km, and up to 130–140 km. Echoes from the ionizing meteor trails are detected by meteor radars (MRs). Since the trails expand in the radial direction and decay in the background atmosphere due to ambipolar diffusion, the amplitude of the MR backscattered radio signal decays in the course of this expansion. The routine MR output includes the meteor count, the height at which a meteor is detected, and the meteor echo decay

time. The measured meteor echo decay time allows the temperature of the neutral atmosphere to be estimated (Hocking, 1999). Thus, meteors serve as sensitive probes of atmospheric conditions in a range of the altitudes not easily studied by other means. MRs have been widely used to monitor the neutral wind velocity and temperature in the mesosphere/low thermosphere region (e.g., Iimura et al., 2011; Lukianova et al., 2017).

The interferometric SKiYMET-type radars primarily serve for determining the atmospheric parameters from the properties of the meteor echo. These radars are not able to determine the radiant of any individual meteor; however, by using the data of elevation and azimuth of the trails, it is nonetheless possible to determine locations of radiants when many meteors have a common origin (Hocking et al., 2001). Some other specific radars such as the Canadian Meteor Orbit Radar (CMOR), the Norwegian high power large aperture radar (Middle Atmosphere Alomar Radar System, MAARSY), and the Southern Argentina Agile Meteor Radar (SAAMER) enable the identification of meteor showers and their properties from the measurements of individual meteor echoes and orbits (Blaauw et al., 2011; Brown et al., 2008, 2010; Bruzzone et al., 2015; Janches et al., 2013; Kero et al., 2012; Pokorný et al., 2017; Schult et al., 2018; Younger et al., 2009). Meteor studies by using high power large aperture radars such as EISCAT 930 MHz (Kero et al., 2008), Aresibo 430 MHz (Mathews et al., 2010), and Jicamarca 50 MHz (Chau & Woodman, 2003; Janches et al., 2014) have been performed. These systems are capable to detect head echoes of the micrometeors.

More than 100 strong and weak streams of different duration have been found, some of them previously unrecognized or poorly characterized. The routine observations of the standard MRs, the number of which constantly grows over the world primarily for meteorological purposes, may also contribute to recognition of the meteor showers and provide some information on the shower members.

Radar and optical observations allow the determination of key properties of the shower meteors like radiant and speed, although some features such as its chemical composition and physical properties are not yet well known. Because of the different nature of parent bodies the properties of the sporadic and shower meteoroids may be inherently different. For instance, Kozlovsky et al. (2016) revealed an indication of unusual properties (mass, density, and/or chemical composition) of the Geminid and Quadrantid meteoroids compared with sporadic ones. The effect is manifested as an enhanced percentage of overdense meteor trails detected by MR during these showers because the algorithm may accept overdense meteors lasting less than few tenths of a second.

The MR count rate may be enhanced during meteor showers. The heights at which MRs detect meteor trails depend on the atmosphere (height profile of density and composition), characteristics of the radar, and properties of the meteoroids (Stober et al., 2014). Height distributions of the meteor trails, therefore, contain some information on the meteoroid mass, speed, density, and composition and hence may be used for recognizing meteor showers.

The purpose of the present paper is to investigate meteor heights and their relations to the properties of the meteoroid. In the study we use the median and quartiles of the meteor height distributions as robust and valuable metrics. Analyzing these quantities we reveal several previously unknown interesting features.

2. Instrument

Routine MR observations at the Sodankylä Geophysical Observatory (SGO, 67°22'N, 26°38'E, Finland) started in December 2008. The all-sky interferometric SKiYMET MR located at SGO (SGO MR) transmits very high frequency waves (36.9 MHz) and receives backscatter from the trails of ionized gas left by meteors entering the atmosphere (meteor echoes). The echoes are detected within a 300-km area around SGO. The radar detects the occurrence of meteors and determines the location of meteor trails, their radial drift speeds, and decay times. Algorithms of the SKiYMET radar signal processing are described in the paper (Hocking et al., 2001). The five-antennae receiving array is arranged as an interferometer, and phase differences in the signals arriving at each of the antennae of the interferometer are used to determine an unambiguous angle of arrival, that is, allows the determination of meteor echo azimuth and elevation angles. The elevation angle measurements in combination with measurements of the echo range allow meteor echo heights to be estimated.

Because of the 2,144-KHz interpulse frequency of MR transmissions the range may be determined with a 70-km ambiguity. To reduce the range ambiguity, the MR data analysis algorithm assumes that meteor

Figure 1. Daily number of meteor echoes detected by Sodankylä Geophysical Observatory meteor radar each year in 2008–2018. The black line shows a median of the daily count. The main meteor showers are denoted.

trails are preferably at heights between 70 and 110 km, so that about 70% of meteors are located unambiguously. For the height distributions in the present paper we use only unambiguous detections, whereas meteor counts (e.g., daily counts in Figure 1) include all detections.

3. Observations

3.1. Daily Meteor Count

The number of meteors detected by the SGO MR varies on an hourly, daily, and monthly basis. Figure 1 depicts the superposed daily number of meteor echoes (the daily MR count) in 2009–2017. Within the annual cycle the daily counts vary between 3,000 and 17,000. Because of astronomical factors (Younger et al., 2009), the highest continuous meteor count rates are observed during the summer months, while a minimum is seen in late winter-spring and the meteor fluxes occurring in the first part of the year are more homogeneous compared to those during the second part.

Scattering of the data in Figure 1 is due to four factors, at least. First, in September 2009 the power of the radar transmission was increased from 7.5 to 15 kW, which resulted in an increased meteor count. Second, because of the SGO position in the region of auroral oval (at the corrected

geomagnetic latitude of 64.1°), the meteor count is sometime reduced because of the radio wave absorption during ionospheric disturbances (Kozlovsky & Lester, 2015). Third, the meteor count is sometimes reduced in winter (late October to early April) because of snowfalls and the snow cover on the antennae. Fourth, there were short intervals when the radar was not operating because of technical problems.

Superposed upon the annual cycle, several distinct episodes of high meteor counts (up to 20,000) during specific meteor showers are seen. The most intense of these are in January (the Quadrantids), August (the Perseids), and December (the Geminids). Other major established meteor showers of the Northern hemisphere, such as the Lyrids in April, Eta Aquarids in May, Arietids in June, Orionids in October, and Leonids in November are less distinctly manifested in the MR count, while the Leonids seem not to be an active meteor stream these years. The Draconid meteor shower which peaked in October 8 does not produce a notable increase in the observed meteor count, although an intense outburst was detected in 2012 (Ye et al., 2013).

3.2. Median and Quartiles Heights

It is known that the statistical height distribution of meteor count rates shows the peak occurrence at approximately 90 km. The height at which a meteor echo is detected depends on the height profile of atmospheric density and the parameters of the meteoroid. For each day we have calculated the median height (M) and the upper and lower quartiles (Uq and Lq , respectively) of the meteor trails detected during a day. At the heights between the upper and lower quartiles 50% of meteors are detected. To calculate these daily parameters we used data from the days when the radar operated more than 22 hr.

Because of the SGO location in auroral zone, the MR frequently accepts nonmeteor targets associated with auroral activity. There might be radar echoes from the ionospheric plasma waves generated due to the Farley-Buneman instability (e.g., Kelley, 2009), which typically occurs during substorms when the ionospheric electric field is strong enough. The Doppler velocity of such targets is up to a few hundred meters per seconds. Mostly these targets are detected at low elevation (below 30°). The other type of nonmeteor echoes is associated with pulsating aurora (Kozlovsky & Lester, 2015). These targets are also observed at low elevation (below 30°), although they have near-zero Doppler velocity. In order to reject the nonmeteor echoes we used only the detections at elevation angle higher than 30° with the Doppler velocity less than 100 m/s.

The top panels in Figure 2 depict the time series of daily M , Uq , and Lq heights. The black curve shows the smoothed variations obtained by applying a 31-point FFT filter. One can see the quasiperiodic seasonal oscillations and also shorter (a few to 10 days) variability. M varies in the range of 87–91 km, while Uq and Lq span the ranges 92–96 and 83–87 km, respectively. The bottom panel in Figure 2 shows the daily meteor counts for the days when the radar was operating longer than 22 hr.

Figure 2. (top) Daily median (M) and upper (Uq) and lower (Lq) heights of meteor detection. The black line depicts a smoothed curve. (bottom) Daily number of meteor echoes detected by the meteor radar. Only data from the days were used when the radar operated more than 22 hr.

To make the seasonal variations of sporadic meteors and the meteor showers more evident, a composite was constructed by superposing daily data from all the years. In such a way the interannual variability is smoothed out while the regular annual peculiarities are manifested. The composite annual variations of the M, Uq, and Lq heights are presented in Figure 3 together with modeled constant levels of atmospheric density above SGO (blue lines). Two interesting features in Figure 3 are worth mentioning. First, and the most important, the signatures of several major meteor showers are clearly identified in the M, Uq, and Lq heights as positive peaks lasting from one to several days. Seven peaks are readily identified in the Uq height (in Figure 3 they are denoted by numbers in red circles), and some of them are also seen in the Lq height. The largest and narrowest peaks occur in the early January, late April, and middle of August. These peaks coincide well in time with the peaks of the Quadrantid, Lyrid, and Perseid meteor showers, respectively. Though smaller in amplitude, other peaks are seen in May (the Eta Aquarids), June (the Arietids), October (the Orionids), and December (the Geminids). There is also one noticeable peak in late January for which, however, no suitable established meteor showers are known. Characteristics of the corresponding meteor showers are given in Table 1. The columns of Table 1 are as follows: dates of the shower, date of the maximal height peak, type of the peak (either it is seen solely in the Uq, or solely in the Lq, or in both metrics), name of the shower, date of its maximum, and shower parameters.

The peaks seen in M, Uq, and Lq heights indicate that the shower meteor trails tend to be detected up to 1 to 2 km higher than sporadic meteors. For a given radar, the detection height of a particular meteor depends on the atmospheric conditions and physical/chemical properties of the meteoroid. It is very unlikely that the sharp changes of meteors' height distribution could occur due to short-time atmospheric changes exactly coinciding with the annual meteor showers. Hence, the larger meteor heights are most probably due to specific properties of the meteoroids of the meteor streams. Furthermore, parameters of height distributions (like width and symmetry) of meteor trails of different showers are different.

The second feature worth noting in Figure 3 is the annual variation of the meteor height. One may expect this variation to be due to the seasonal change of the atmospheric density. This is demonstrated by comparison with the lines of constant atmospheric density (isobars) calculated for the SGO site using the NRLMSISE-00 model (Picone et al., 2002) as a reference atmosphere (the blue lines in Figure 3). At altitudes below 90 km the model shows a seasonal tendency of the density to decrease in winter and increase in summer. Above 90 km the tendency is opposite. Except the peaks associated with the meteor showers, the observed heights of M, Lq, and Uq generally follow the model isobars, although with certain discrepancies to be discussed below in section 4.

Figure 3. The 9-year composite of the median (M) and upper (Uq) and lower (Lq) heights. The numbers in the red circles correspond to the first column of Table 1. The blue lines show the levels of constant atmospheric density (in $10^{-10} \text{ g/cm}^{-3}$) calculated for the Sodankylä Geophysical Observatory site using the NRLMSISE-00 model.

3.3. Thickness of Ablation Layer

To distinguish shower meteors which penetrate to lower altitudes from those producing ionization trails at the higher altitudes, in Table 1 the peaks seen only in the Uq height are labeled by “U” and those seen only in the Lq height are labeled by “L.” Letters “UL” denote the peaks seen in both the upper and lower quartiles. The Lyrids (late April, #3 in Table 1) and Orionids (late October, #7) burn up within atmospheric layers, which

Table 1

Characteristics of the Meteor Showers: Ordinal Number Since the Beginning of the Year, Date of the Shower, Date of the Maximal Height Peak, Type of the Peak (See Section 3.3), Name of the Shower, Date of Its Maximum, Right Ascension RA, Declination D, Geocentric Velocity V_G , and Zenithal Hourly Rate ZHR

#	Dates of shower (date of maximum)	Type	Showers	Peak	RA	D	V_G	ZHR
1	2–4 January (3)	UL	Quadrantids	4 Jan	15	+49	41	130
2	26–30 January (29)	UL	(?) Alpha Leonids (?) January Nu Orionids	24–31 January 28 January	10 6	+9 +12	30 12	
3	21–23 April (22)	U	Lyrids	22 Apr	18	+32	47	13
4	3–8 May (6)	U	Eta Aquariids	6 May	23	–1	65	28
5	4–16 June (9)	UL	Arietids Daytime Zeta Perseids	7 June 9 June	3 4	+24 +23	37 27	54 20
6	8–16 August (12)	U	Perseids	13 August	3	+58	59	84
7	19–25 October (23)	U	Orionids	22 October	6	+16	66	25
8	11–16 December (13)	UL	Geminids	14 December	7	+33	35	120

Figure 4. The 9-year composite of the width of the atmospheric layer within which 50% of meteoroids ablate. The blue line corresponds to the NRLMSISE-00 model.

appear to be thicker than the layers where the sporadic meteors usually ablate. For these showers an increase is observed in the Uq height, while the Lq height stays the same as that for the sporadic meteors. For the Geminids (December, #8) the thickness of ablation layer is reduced because of the larger Lq height. Some other showers (the Quadrantids in January, the unknown shower in late January, and the Arietids in June) are detected within the atmospheric layers which are located ~ 1 km higher than that for the sporadic meteors (see Figure 3). However, the thickness of the layers for the shower members and sporadic meteors stays approximately the same. The peak corresponding to the Perseids (August, #6) is observed in both the Uq and Lq heights, although it is more prominent (>2 km) in the Uq height. As a result, the thickness of the ablation layer is considerably enhanced.

The thickness of the atmospheric layer in which the meteoroids ablate depends primarily on the background atmosphere. However, the signatures of meteor showers are also seen in this parameter. Figure 4 depicts, as a composite year, the mean difference between daily Uq and Lq (i.e., the thickness of the layer within which 50% of the trails are detected). The vertical gray lines indicate a standard deviation. The shape of the annual variation of the thickness generally agrees with the NRLMSISE-00 prediction of the seasonal change of atmospheric density (shown by the blue line). The amount of air in the column where meteors ablate does not vary considerably, although the thickness of the layer (i.e., the column width) changes from 9 km in summer to 14 km in winter.

Note that the thickness of the air column within which the meteor ablation layer is located may increase in association with dynamic impact in the winter stratosphere since sudden stratospheric warmings (SSWs) often occur in January. During the period of observations two major SSWs occurred in 2009 and 2013 and a medium SSW occurred in 2010. During SSW2009, which occurred under conditions of very low solar activity, a pronounced mesospheric cooling has been observed by SGO MR (Lukianova et al., 2015). In 2013, at the peak of solar cycle 24, the mesospheric temperature perturbation associated with a major SSW was marginal. The atmospheric density at the mesosphere/low thermosphere heights responds to the stratospheric heating by a considerable altitude variation of constant density surfaces due to elevated stratopause (i.e., Zülicke & Becker, 2013). To check the SSW effect, temporal variations in the atmospheric density at the meteor heights retrieved from the Sounding of the Atmosphere using Broadband Emission Radiometry instrument on board the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (Russell III et al., 1999) over the SGO site have been analyzed. It appears that in association with a major SSW which is accompanied by a pronounced mesospheric cooling, the neutral density isolines are shifted to lower altitudes by about 1 and 3 km at 90 and 80 km height, respectively (not shown). As a result the distance between the constant density surfaces increases; that is, the SSW effect may mimic the meteor shower effect in the ablation layer thickness. However, since SSWs occur at a different time, this meteorological effect is smoothed and not seen in the composite year presented in Figure 4.

Short-time deflections from the smooth annual variation of the column height appear solely during meteor showers. The thickness of the ablation layer increases in August (Perseids), October (Orionids), and April (Lyrids), while it decreases during Geminids (December) and Quadrantids (early January). Remarkably, there is a noticeable increase of column height in the middle of November. These dates correspond well with the Leonid meteor shower, although this shower is hardly identified in the median and quartiles heights in Figure 3. For the meteor showers numbered in Table 1 as #2, 4, and 5 (late January, early May, and June) the layer thickness also increases, but the effect is less significant.

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4. Interpretation and Discussion

In the analysis presented above, we used the median and upper and lower quartile heights of MR detections as simple and robust parameters for studying the height distribution of meteor ablation. We show that the M,

Uq, and Lq heights may be used to identify periods of specific meteor showers and to infer the properties of meteoroids of the showers.

4.1. Identification of Meteor Showers

It is remarkable that all the northern hemisphere regular meteor showers with zenithal hourly rate (ZHR) larger than 12 have been identified in the height distribution data. Note that being primarily related to visual estimation of the meteor count, the ZHR is defined for a specific mass range, which is not necessary the exact mass range detected by the MR. However, the shower obviously contains the meteors detectable by MR. Most of the showers are manifested as sharp peaks in the upper quartile, whereas the signature of Geminids appears preferably in the lower quartile and the Leonids are indicated in the width of ablation layer.

Possible signatures of a meteor shower were identified on 26–30 January, which does not correspond to any established meteor shower to be observed at a given latitude. Based on the dates we may speculate that two possible meteor streams might be responsible for the observed effect. The first one is the Alpha Leonid shower which peaks in the last week of January (Kronk, 2014). The evidence for this stream's existence comes from the radio meteor project conducted during the 1960s (Sekanina, 1973, 1976). The second possible candidate is the January Nu Orionid asteroidal meteor stream occurring during 1 January to 4 February with a peak on 28 January (Jenniskens, 2006). To solve this problem, data from other MRs around the globe as well as a source radiant, velocity, and orbital data in solar longitude are required. However, without sufficient astronomical information, we are not able to prove that this is a new shower.

Data from the identified meteor showers (and possible candidates for the late January shower) are given in Table 1. The data are taken from Jenniskens (2006), except the Alpha Leonid shower data cited from Kronk (2014). The parameters are dates of peaks, right ascension, declination, geocentric velocity, and ZHR. Looking at the velocity data in Table 1, we notice that for the showers identified in the upper quartile (classified by "U") and hence ablated at higher altitudes, the speed of meteoroids is 50–70 km/s, whereas the meteors detected at lower heights (classified by "L" or "UL") have a smaller speed, typically 30–40 km/s. This remarkable feature is discussed in the next section.

4.2. Properties of Meteoroids

Smooth seasonal variations of the meteor height are basically variations of the height of sporadic meteors. On the seasonal background, meteor showers are readily identified as a sharp rise of the altitudes at which they burn up. Likely due to their specific properties, the shower members tend to burn up at lower atmospheric density than the sporadic meteors.

Detection of the shower members at higher altitudes is obviously due to easier ablation of the meteor material. The primary equations describing the evolution of a meteoroid entering the Earth's atmosphere are the equation of braking and the equation of mass loss. Solving these equations, Bronshten (1983) has shown that motion of a particular meteoroid is essentially determined by three parameters: the speed of the meteoroid at the atmospheric boundary, its initial mass (or its density), and angle of trace to the vertical. If two meteoroids with the same speed but different mass and angle enter the atmosphere, they will break and lose the mass following the same law but at different heights. For the height interval of 80–100 km (where the atmospheric height scale is 6 km), if one meteoroid is twice as heavy as the other, the former will reach the same degree of ablation about 1.4 km lower than the latter. The same height difference occurs if the density of the two meteors differs by a factor of $\sqrt{2}$. The meteor density is known poorly, but these estimations allow us to presume that the detection of a meteor shower at higher altitudes is due to the presence of lighter meteoroids, such as like a dust cloud (Opic, 1955). Different chemical compositions as well as a fragmentation of the meteoroid into its smaller subunits may also play a role.

It has been proposed in several reports that the shower members are small and of low density. Jacchia et al. (1967) have found that Orionids only need a relatively small amount of air to slow the meteoroids down and end above 90 km. The Aquariids and Quadrantids are efficiently decelerated in the atmosphere with a high fragmentation rate. The Arietids were found to peak at altitude of about 92 km with a narrow distribution of heights, whereas the Quadrantids of a similar size are observed at about 95 km (McKinley, 1961). Properties of the Draconids are likely close to those of sporadic meteors. Our present observations also agree with the finding of Kozlovsky et al. (2016) that the height distribution of the Geminids has a maximum at 91 km, whereas

the sporadic background meteors on 20–22 December show a maximum at 88 km. On average, the Geminids trails were detected 3 km higher than sporadic meteors, which results in about a 1 km higher median of the net (i.e., the shower plus sporadic) meteor distribution during Geminids on 12–14 December (indicated by “8” in Figure 3). Stober et al. (2012) simulated the effects of meteor velocity and neutral atmospheric density on meteor peak height and found that a 1-km/s difference in the initial velocity of a meteoroid with an entry angle of 45° translates into a detection height difference of approximately 0.3–0.4 km.

The comprehensive MR systems (CMOR, MAARSY, and SAAMER) are designed to measure the individual meteor orbits. Among a number of meteoroid characteristics the mass distribution index is calculated. A higher mass index indicates that there is more mass in smaller particles, and a lower mass index indicates that there is more mass in larger particles. It was shown that the Quadrantids and Geminids consistently have the lowest mass indices, whereas the Eta Aquariids and Orionids have peak mass indices slightly higher (Blaauw et al., 2011). The presence of meteoroids in streams having masses as low as 10^{-9} kg to as small as 10^{-10} kg, for faster meteor showers, is directly demonstrated by their visibility in the head echo data. The MAARSY data provide the mass index of about 1.5 for Perseids, Quadrantids, and Geminids, while the Orionids show a much steeper mass index of about 2.0, suggesting smaller meteoroids (Schult et al., 2018). Using the CMOR facility Bruzzone et al. (2015) studied the Daytime Arietid meteor shower. This survey recorded orbits having representative masses of $8 \cdot 10^{-8}$ kg and sizes of ≈ 0.4 mm; the mass index of the stream is about 1.6. The CMOR radar provides velocity for more than 100 of the detected streams contained particles with mass near 10^{-7} kg. In particular, the velocity at the time of maximum of the Quadrantids, Geminids, Eta Aquariids, and Orionids is about 42, 35, 64, and 65 km/s, respectively (Brown et al., 2008, 2010). The quantitative estimate of meteor velocity is confirmed by the southern hemisphere radar observations, although the overall tendency for CMOR’s velocity to be slightly higher is mentioned (Pokorný et al., 2017).

A meteor shower direction and velocity may provide important information on the narrow shower source region and the shower parent body. Using the Shigaraki Middle and Upper Atmosphere Radar in Japan, Kero et al. (2012) investigated the radiant distribution (the radiant is expressed in terms of the Sun-centered ecliptic longitude and latitude and geocentric velocity) and diurnal rate for more than 10^5 sporadic and shower meteors. For sporadic meteors, the characteristics of six main sources were identified along with several compact radiant concentrations due to meteor showers.

Using statistical techniques applied to the SAAMER observations Janches et al. (2013) identified the radiants of 32 showers, while Pokorný et al. (2017) found the characteristics of 58 showers, approximately a half of which are not from the International Astronomical Union catalogue. Using MR observations collected during at Davis Station, Antarctica, and Darwin, Australia, 37 distinct meteor showers were detected, including 9 not in the International Astronomical Union catalogues, and their radiant and velocity were estimated (Younger, Astin, et al., 2009). For the Quadrantids, Geminids, and Orionids the velocity estimate is 41, 35, and 61 km/s, respectively. The peak velocity for the sporadic meteors is about 20 km/s (Nesvorný et al., 2011). These values are related to the height at which meteors start to ablate. Some kind of deceleration occurs during the process of ablation and at any one height the spread in velocity can be as large as several km/s (Cervera et al., 1997).

Comets emit many small dust grains (40–100 μm). The small grains are ejected with higher speed and are pushed more by solar radiation force (Jenniskens, 2006). Entering the atmosphere at higher speed the meteoroid ablates in less dense air, hence, at a higher altitude. Indeed, this agrees with the result of the present paper that larger speed meteors (50–70 km/s) are detected in the upper quartile, whereas signatures of slower meteors (30–40 m/s) are more distinct in the lower quartile. Ceplecha et al. (1998) predicted that the ablation heights nonlinearly increase as a function of a faint meteor speed below ~ 30 km/s, while for higher speeds the dependence tends to become linear.

The parent bodies of the majority of meteor showers are comets. In particular, the Perseids are caused by the largest comet Swift-Tuttle, while the parent body of the Orionids is the comet Halley. The parent body of Geminids is the Phaeton asteroid, the nature of which, however, is similar to a comet because its material is evaporated while the asteroid approaches to the Sun. Thus, we may expect that speeds of shower meteors are typically larger than that of sporadic background. This is the most likely explanation for the observational results of the present study. This relatively simple method of recognition of the meteor streams from the much stronger sporadic background may contribute to the recognition of the

candidates for previously unknown streams. An unequivocal identification needs the geocentric velocity and orbit information, though.

5. Conclusions

Data from the MR observations in SGO (67°N) during 2008–2017 were used to study the height distribution of ionized meteor trails. Generally, the annual variation of the height distribution agrees with the annual variation of the atmospheric density predicted by the NRLMSISE-00 model. However, meteoroids belonging to showers likely produce ionization trails at higher altitudes compared to the sporadic meteors. The effect is manifested as short-time (one to few days) elevations of the median and quartiles of the meteor height distribution. This can be used (1) to identify periods of specific meteor showers and (2) to infer physical properties of meteoroids of the showers.

1. Using this method, we have identified all the main northern hemisphere regular meteor showers, whereas only a few of these showers are seen in the daily MR counts. Most of the showers (Quadrantids, Lyrids, Eta Aquariids, Arietids and/or Daytime Zeta Perseids, Perseids, and Orionids) are manifested as sharp peaks in the upper quartile, whereas the signature of Geminids appears preferably in the lower quartile. Additionally, signatures of one more meteor shower are identified on 26–30 January, which does not correspond to any established shower to be observed at the given latitude. Looking through the northern hemispheric database several candidates can be found, but just from the date, it is impossible to link the observations to the database. Among hypothetical candidates there may be the Alpha Leonid shower peaking in the last week of January and the January Nu Orionid asteroidal meteor stream occurring during 1 January to 4 February with a peak on 28 January.
2. We found that for the showers identified in the upper quartile and hence ablated at higher altitudes, the speed of meteoroids is 50–70 km/s, whereas the meteors detected at lower heights have smaller speed of about 30–40 km/s.

A notable result is a new simple method of recognition of the meteor streams from the much stronger sporadic background. The presented method is only sensitive to meteor showers having properties differing from the sporadic background. Usually, it is very difficult to classify the properties of the meteoroids.

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References

- Blaauw, R. C., Campbell-Brown, M. D., & Weryk, R. (2011). A meteoroid stream survey using the Canadian Meteor Orbit Radar—III. Mass distribution indices of six major meteor showers. *Monthly Notices of the Royal Astronomical Society*, 414(4), 3322–3329. <https://doi.org/10.1111/j.1365-2966.2011.18633.x>
- Bronshen, V. A. (1983). *Physics of meteoric phenomena* (356 pp.). Dordrecht, Holland: Kluwer.
- Brown, P., Weryk, R., Wong, D., & Jones, J. (2008). A meteoroid stream survey using the Canadian Meteor Orbit Radar: I. Methodology and radiant catalogue. *Icarus*, 195(1), 317–339. <https://doi.org/10.1016/j.icarus.2007.12.002>
- Brown, P., Wong, D., Weryk, R., & Wiegert, P. (2010). A meteoroid stream survey using the Canadian Meteor Orbit Radar II: Identification of minor showers using a 3D wavelet transform. *Icarus*, 207(1), 66–81. <https://doi.org/10.1016/j.icarus.2009.11.015>
- Bruzzone, J. S., Brown, P., Weryk, R. J., & Campbell-Brown, M. D. (2015). A decadal survey of the daytime Arietid meteor shower using the Canadian Meteor Orbit Radar. *Monthly Notices of the Royal Astronomical Society*, 446(2), 1625–1640. <https://doi.org/10.1093/mnras/stu2200>
- Ceplecha, Z., Borovička, J., Elford, W. G., ReVelle, D. O., Hawkes, R. L., Porubčan, V. ě., & Šimek, M. (1998). Meteor phenomena and bodies. *Space Science Reviews*, 84(3/4), 327–471. <https://doi.org/10.1023/A:1005069928850>
- Cervera, M. A., Elford, W. G., & Steel, D. I. (1997). A new method for the measurement of meteor speeds: The pre-t0 phase technique. *Radio Science*, 32(2), 805–816. <https://doi.org/10.1029/96RS03638>
- Chau, J., & Woodman, R. F. (2003). Observations of meteor-head echoes using the Jicamarca 50 MHz radar in interferometer mode. *Atmospheric Chemistry and Physics*, 3(6), 6063–6091. <https://doi.org/10.5194/acpd-3-6063-2003>
- Hocking, W. K. (1999). Temperatures using radar-meteor decay times. *Geophysical Research Letters*, 26(21), 3297–3300. <https://doi.org/10.1029/1999GL003618>
- Hocking, W. K., Fuller, B., & Vandepeer, B. (2001). Real-time determination of meteor-related parameters utilizing modern digital technology. *Journal of Atmospheric and Solar-Terrestrial Physics*, 63(2–3), 155–169. [https://doi.org/10.1016/S1364-6826\(00\)00138-3](https://doi.org/10.1016/S1364-6826(00)00138-3)
- Iimura, H., Fritts, D. C., Tsutsumi, M., Nakamura, T., Hoffmann, P., & Singer, W. (2011). Long-term observations of the wind field in the Antarctic and Arctic mesosphere and lower-thermosphere at conjugate latitudes. *Journal of Geophysical Research*, 116, D20112. <https://doi.org/10.1029/2011JD016003>
- Jacchia, I. G., Verniani, F., & Briggs, R. E. (1967). An analysis of the atmospheric trajectories of 413 precisely reduced photographic meteors. *Smithsonian Contrib. Astrophysics*, 10(1), 1–139. <https://doi.org/10.5479/si.00810231.10-1.1>
- Janches, D., Hormaechea, J., Brunini, C., Hocking, W., & Fritts, D. (2013). An initial meteoroid stream survey in the southern hemisphere using the Southern Argentina Agile Meteor Radar (SAAMER). *Icarus*, 223(2), 677–683. <https://doi.org/10.1016/j.icarus.2012.12.018>
- Janches, D., Plane, J. M. C., Nesvorn, D., Feng, W., Vokrouhlick, D., & Nicolls, M. J. (2014). Radar detectability studies of slow and small zodiacal dust cloud particles. I. The case of Arecibo 430 MHz meteor head echo observations. *Astrophysical Journal*, 796(1), 41. <https://doi.org/10.1088/0004-637X/796/1/41>

- Jenniskens, P. (2006). *Meteor showers and parent comets* (p. 790). Cambridge: Cambridge University Press.
- Kelley, M. C. (2009). *The Earth's ionosphere: Plasma physics and electrodynamics* (2nd ed., p. 536). New York: Elsevier.
- Kero, J., Szasz, C., Nakamura, T., Meisel, D. D., Ueda, M., Fujiwara, Y., et al. (2012). The 2009–2010 MU radar head echo observation programme for sporadic and shower meteors: Radiant densities and diurnal rates. *Monthly Notices of the Royal Astronomical Society*, 425(1), 135–146. <https://doi.org/10.1111/j.1365-2966.2012.21407.x>
- Kero, J., Szasz, C., Pellinen-Wannberg, A., Wannberg, G., Westman, A., & Meisel, D. D. (2008). Determination of meteoroid physical properties from tristatic radar observations. *Annales Geophysicae*, 26(8), 2217–2228. Retrieved from www.ann-geophys.net/26/2217/2008/, <https://doi.org/10.5194/angeo-26-2217-2008>
- Kozlovsky, A., & Lester, M. (2015). On the VHF radar echoes in the region of midnight aurora: Signs of ground echoes modulated by the ionosphere. *Journal of Geophysical Research: Space Physics*, 120, 2099–2109. <https://doi.org/10.1002/2014JA020715>
- Kozlovsky, A., Lukianova, R., Shalimov, S., & Lester, M. (2016). Mesospheric temperature estimation from meteor decay times during Geminids meteor shower. *Journal of Geophysical Research: Space Physics*, 121, 1669–1679. <https://doi.org/10.1002/2015JA022222>
- Kronk, G. W. (2014). *Meteor showers: An annotated catalog* (p. 361). New York: Springer. <https://doi.org/10.1007/978-1-4614-7897-3>
- Lewis, J. S. (2000). *Comet and asteroid impact hazards on a populated Earth: Computer modeling* (p. 200). San Diego: Academic Press.
- Lukianova, R., Kozlovsky, A., & Lester, M. (2017). Climatology and inter-annual variability of the polar mesospheric winds inferred from the meteor radar observations over Sodankylä (67N, 26E) during solar cycle 24. *Journal of Atmospheric and Solar-Terrestrial Physics*, 171, 241–249. <https://doi.org/10.1016/j.jastp.2017.06.005>
- Lukianova, R., Kozlovsky, A., Shalimov, S., Ulich, T., & Lester, M. (2015). Thermal and dynamical perturbations in the winter polar mesosphere-lower thermosphere region associated with sudden stratospheric warmings under conditions of low solar activity. *Journal of Geophysical Research: Space Physics*, 120, 5226–5240. <https://doi.org/10.1002/2015JA021269>
- Mathews, J. D., Briczinski, S. J., Malhotra, A., & Cross, J. (2010). Extensive meteoroid fragmentation in V/UHF radar meteor observations at Arecibo Observatory. *Geophysical Research Letters*, 37, L04103. <https://doi.org/10.1029/2009GL041967>
- McKinley, D. W. R. (1961). *Meteor science and engineering*. New York: McGraw-Hill.
- Nesvorny, D., Janches, D., Vokrouhlicky, D., Pokorný, P., Bottke, W. F., & Jenniskens, P. (2011). Dynamical model for the zodiacal cloud and sporadic meteors. *The Astrophysical Journal*, 743(2), 129. <https://doi.org/10.1088/0004-637X/743/2/129>
- Opic, E. J. (1955). Meteor radiation, ionization and atomic luminous efficiency. *Proceedings of the Royal Society A*, 230, 463–501. <https://doi.org/10.1098/rspa.1955.0147>
- Picone, J. M., Hedin, A. E., Drob, D. P., & Aikin, A. C. (2002). NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues. *Journal of Geophysical Research*, 107(A12), 1468. <https://doi.org/10.1029/2002JA009430>
- Pokorný, P., Janches, D., Brown, P. G., & Hormaechea, J. L. (2017). An orbital meteoroid stream survey using the Southern Argentina Agile MEteor Radar (SAAMER) based on a wavelet approach. *Icarus*, 290, 162–182. <https://doi.org/10.1016/j.icarus.2017.02.025>
- Russell, J. M. III, Mlynarczyk, M. G., Gordley, L. L., Tansock, J. J., & Esplin, R. W. (1999). An overview of the SABER experiment and preliminary calibration results. *SPIE*, 3756, 277–288.
- Schult, C., Brown, P., Pokorný, P., Stober, G., & Chau, J. L. (2018). A meteoroid stream survey using meteor head echo observations from the Middle Atmosphere ALOMAR Radar System (MAARSY). *Icarus*, 309, 177–186. <https://doi.org/10.1016/j.icarus.2018.02.032>
- Sekanina, Z. (1973). Statistical model of meteor streams. III—Stream search among 19303 radio meteors. *Icarus*, 18(2), 253–284. [https://doi.org/10.1016/0019-1035\(73\)90210-8](https://doi.org/10.1016/0019-1035(73)90210-8)
- Sekanina, Z. (1976). Statistical model of meteor streams. IV—A study of radio streams from the synoptic year. *Icarus*, 27, 265–321.
- Stober, G., Jacobi, C., Matthias, V., Hoffmann, P., & Gerding, M. (2012). Neutral air density variations during strong planetary wave activity in the mesopause region derived from meteor radar observations. *Journal of Atmospheric and Solar - Terrestrial Physics*, 74, 55–63. <https://doi.org/10.1016/j.jastp.2011.10.007>
- Stober, G., Matthias, V., Brown, P., & Chau, J. L. (2014). Neutral density variation from specular meteor echo observations spanning one solar cycle. *Geophysical Research Letters*, 41, 6919–6925. <https://doi.org/10.1002/2014GL061273>
- Ye, Q., Wiegert, P., Brown, P., Campbell-Brown, M. D., & Weryk, R. (2013). The unexpected 2012 Draconid meteor storm. *Monthly Notices of the Royal Astronomical Society*, 437(4), 3812–3823. <https://doi.org/10.1093/mnras/stt2178>
- Younger, J. P., Reid, I. M., Vincent, R. A., Holdsworth, D. A., & Murphy, D. J. (2009). A southern hemisphere survey of meteor shower radiants and associated stream orbits using single station radar observations. *Monthly Notices of the Royal Astronomical Society*, 398(1), 350–356. <https://doi.org/10.1111/j.1365-2966.2009.15142.x>
- Younger, P. T., Astin, I., Sandford, D. J., & Mitchell, N. J. (2009). The sporadic radiant and distribution of meteors in the atmosphere as observed by VHF radar at Arctic, Antarctic and equatorial latitudes. *Annales Geophysicae*, 27(7), 2831–2841. <https://doi.org/10.5194/angeo-27-2831-2009>
- Zülicke, C., & Becker, E. (2013). The structure of the mesosphere during sudden stratospheric warmings in a global circulation model. *Journal of Geophysical Research: Atmospheres*, 118, 2255–2271. <https://doi.org/10.1002/jgrd.50219>