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Population of hyperbolic meteoroids

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The presence of hyperbolic orbits among detected meteors started an assiduous search for interstellar meteoroids, as a hyperbolic excess above the escape velocity with respect to the Sun reveals a possible interstellar origin. Research into interstellar meteoroids has produced controversial results about their contribution to the Solar System meteoroid population, and in spite of great progress in the development of observational techniques, this problem still remains. Our study, based on analyses of hyperbolic meteor orbits from various catalogues of meteors obtained by different techniques, shows, from the statistical point of view, that the number of possible interstellar meteoroids among the hyperbolic orbits is extremely small. The biggest obstacle in this study is the accuracy of velocity measurements and determinations. The uncertainties which result from measuring errors make discriminating interstellar meteors among hyperbolic orbits very difficult, and even impossible if, in connection with their orbital and geophysical parameters, individual cases are not checked. In most cases, possible interstellar meteoroids can be found only within the error bars of the determined heliocentric velocity. As the value of the heliocentric velocity is very sensitive to the value of semimajor axis, the errors can transfer the orbit over the parabolic limit. It was shown that the hyperbolicity of the vast majority of meteor orbits in the catalogues investigated is the result of inaccurate velocity determination. This conclusion does not necessarily imply large measurement errors, since, especially near the parabolic limit, even a small error in the value of the heliocentric velocity of a meteor can create an artificial hyperbolic orbit that does not really exist. The "very high" meteor velocities produce an apparent hyperbolic population.

1 Introduction

The problem of the contribution of interstellar particles to the Solar System meteoroid population has always been contentious, and, in spite of great progress in the development of observational techniques, it remains so. To the extent that the Solar System is not an isolated system, its interaction with the interstellar medium should lead to the presence of interstellar particles. The substantial problem, whether meteors arriving from outside the heliosphere are present among the registered hyperbolic orbits and, if so, what their frequency is as a function of their masses and velocities, has led to many searches using both Earth-based or space-born observations, with controversial results.

In light of this, it is interesting to note that the general opinion during the first half of the last century was that the majority of meteors are of interstellar origin (Hoffmeister, 1937). In the first catalogue of bolides by Hoffmeister from 1925, 79% of meteor orbits were found to be hyperbolic. The results of Öpik's Arizona meteor expedition of 1931–33 reinforced this opinion (Öpik, 1934). Later, by means of Super-Schmidt cameras, which allowed a much more precise determination of bolide velocities, the results from the Harvard photographic program published by Jacchia and Whipple (1961) gave so few hyperbolic velocities that they raised the question of whether interstellar meteors existed at all. This history may be in some way instructive for the latest conclusions about the detection of interstellar particles, without giving reliable results on the velocity determination of those particles (for more detail, see Hajduk, 2001), because accurate velocity measurements lead to solutions to this problem.

Here, we present an overview of previous studies related to interstellar particles as well as of our own reported results, obtained from several catalogues of meteors observed by different techniques, which allow us to reach some solid conclusions. This paper demonstrates that the number of possible interstellar meteoroids among hyperbolic orbits in the registered data is extremely small, and that the number of hyperbolic orbits thus qualified due to erroneous velocity determination is large.

2 Previous studies

The first detections of interstellar particles were reported in results obtained from space-born observations about 20 years ago. Grün (1993) concluded that the dust detectors on board the Ulysses space probe had identified interstellar dust particles passing through the outer Solar System on hyperbolic trajectories, and that they could be easily distinguished from interplanetary dust by their retrograde trajectories (Grün, 1994). Around the same time, Baggaley et al. (1993), on the basis of observations from the Advanced Meteor Orbit Radar (AMOR), dealt with the influx of meteoroids with hyperbolic heliocentric orbits and with extremely high velocities. Later they reported the radar detection of interstellar meteoroids (in the mass range of 10^{-10}–

10^{-7} kg) in the Earth's atmosphere (Baggaley, 1999), which originated from a few discrete sources in the vicinity of the Sun (Taylor et al., 1996).

The search for interstellar particles has continued over the last two decades, using different observation techniques, and has attempted to map the galactic sources of interstellar dust (Baggaley et al., 2007). The contribution of interstellar particles to the interplanetary meteoroid population was found to be much higher for small particles (from the mass range between 10^{-19} and 10^{-11} kg) obtained from cosmic dust detectors (Krüger et al., 2007), in comparison with the range of larger meteoroid particles ($m > 10^{-9}$ kg) obtained from radar (Weryk and Brown, 2005), photographic (Hajduková, 1994; 2008) and video (Hawkes and Woodworth, 1997; Hawkes et al., 1999; Hajduková, 2011; Musci et al., 2012) observations. This contradiction can be explained by the different mass distribution of interstellar and interplanetary particles along the broad scale of mass exceeding 20 orders of magnitude (Hajduková and Hajduk, 2006). Interstellar dust flux could also change according to the condition of interplanetary magnetic fields. While the flux of larger interstellar meteoroid particles ($m > 10^{-7}$ kg) was found to be close to zero (Hajduková, 1994; 2011; Musci et al., 2012), the results from the Ulysses and Galileo space probes show a predominance of interstellar particles (in the mass range 10^{-17}–10^{-15} kg) in the outer Solar System (Grün et al., 1997). The latter argue for their interstellar origin using three criteria: their retrograde trajectories, high impact speed, and independence from the ecliptic latitude (Krüger et al., 1999; Grün et al., 2000). The mass distribution of the measured interstellar particles shows a dropoff at small masses ($m < 10^{-17}$ kg), explained by Baguhl et al. (1995) as indicating that smaller interstellar dust particles are kept out of the heliosphere by defocusing Lorentz forces.

It has to be noted that the authors of the above-mentioned studies designated particles as "interstellar" mainly on the grounds that they correspond either to hyperbolic orbits or to hyperbolic velocities. Naturally, the hyperbolic orbits (with eccentricity $e > 1$ and semimajor axis $a < 0$) or hyperbolic velocities do not necessarily entail interstellar particles; they rather represent the highest upper limit for them. Thus, the real flux of interstellar particles along the mass scale still remains unclear. An overview of the eventual fluxes of interstellar particles along the broad scale of mass exceeding 20 orders of magnitude was reported in our earlier studies (Hajduková and Paulech, 2002; Hajduková and Hajduk, 2006).

3 Data of meteor orbits used

We made a detailed examination of hyperbolic orbits from the various catalogues of meteors which were observed using different techniques, and reported the results in several studies. For the analysis, 2910 meteor orbits from the photographic catalogue of the IAU Meteor Data Center (Lindblad, 1987), as well as the updated version of this catalogue, which contains 4581 orbits (Lindblad et al., 2005), were used. We also analyzed 62 906 radar meteors of the IAU Meteor Data Center (Lindblad, 2003), with a special emphasis on the 39 145 orbits of the Harvard Meteor Project. Moreover, 64 650 video observed meteors from the SonotaCo catalogue (SonotaCo, 2009) and, separately, a quality selection of them (Vereš and Tóth, 2010) were used in our search for interstellar meteors.

4 The velocity determination

The inaccuracy in the heliocentric velocity is a significant source of uncertainty in semimajor axes determination, and it can easily push the orbit over the parabolic limit and create a group of meteoroids apparently moving in hyperbolic orbits. There are different reasons for an error in the heliocentric velocity, the value of which is very sensitive to the value of semimajor axis a, the orbital element most intimately connected with the origin of meteor particles. The process of velocity determination proceeds in several steps, starting from the measured atmospheric velocity, and on through the non-atmospheric velocity and the geocentric velocity, in order to determine the heliocentric velocity of the meteoroid. Each of these steps tends to increase the inaccuracy of the initial data. Different errors—such as the effects of the instruments used; measurement errors; irregularities in the atmospheric deceleration; and errors in timing and radiant determination, which affect the subtraction of the motion of the Earth from the geocentric velocity—vary in importance, and cannot readily be separated from one another. At the end, the error in the heliocentric velocity v_H can easily exceed 1 km/s, which corresponds to about 0.08–0.09 AU^{-1} in $1/a$ (Kresák, 1992). The resulting hyperbolicity cannot be attributed to the interstellar origin of the particle without a proper error analysis. Such large errors transfer orbits of meteoroids with high heliocentric velocities over the parabolic limit. This is well observed in the population of cometary meteoroids with nearly unbound orbits, and explains the massive number of hyperbolic orbits among the Perseids in our data in all catalogues we investigated.

The velocity distribution for all photographic meteors from the IAU Meteor Data Center (MDC) in Figure 1 shows a widely scattered Gaussian distribution with heliocentric velocities reaching values of 75 km/s. The detailed examination (Hajduková, 2008) showed that the errors in the determination of v_H in some cases may be as large as 10 km/s. This explains the great number (11.5%) of orbits with $e > 1$ in the catalogue, the hyperbolicity of which is a consequence of measurement errors.

A total of 39 145 radar meteors from the Harvard catalogue of the IAU MDC and 970 hyperbolic meteors

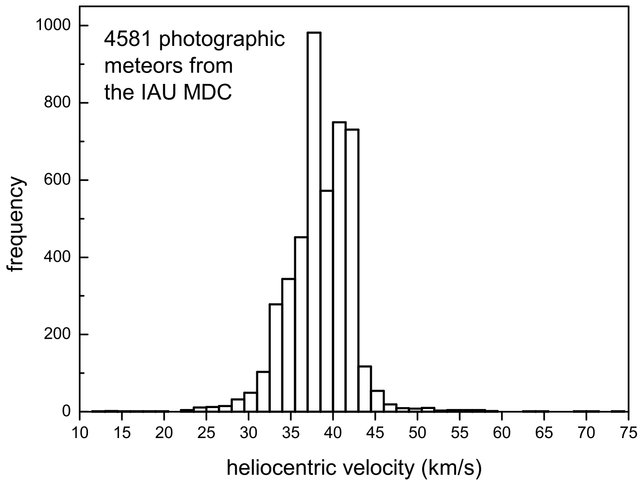

Figure 1 – Distribution of heliocentric velocities of all photographic meteors from the IAU MDC shows a scattered Gaussian distribution, which, in the vicinity of the parabolic limit, results in the designation of a "hyperbolic orbit".

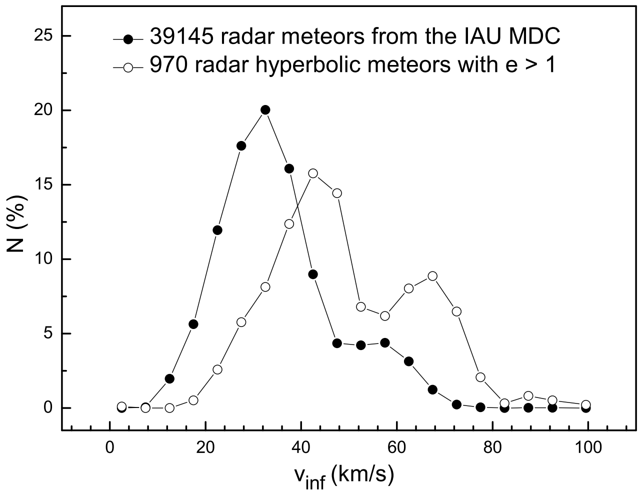

Figure 2 – The velocity distribution (normalized to 100%) of all meteors and hyperbolic meteors from the Harvard sample of the radar catalogue of the IAU MDC (Hajduková and Paulech, 2007).

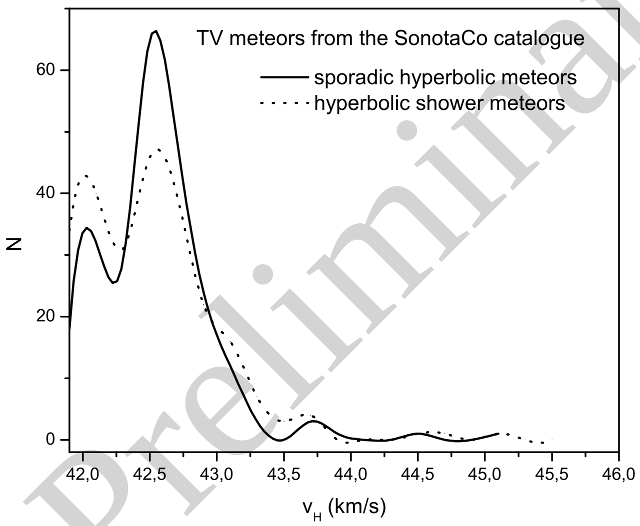

Figure 3 – The velocity distribution of meteors with hyperbolic excesses from the SonotaCo database plotted separately for sporadic and shower meteors.

from the same sample show the same velocity distribution (in Figure 2, non-atmospheric velocities are visualized in the same proportion), but with velocities of about 10 km/s higher. The observed shift between both sets of data is caused by a high spread in velocity determination—suggesting large errors in the velocity determination (Hajduková and Paulech, 2007), shifting a part of the data through the hyperbolic limit.

The spread in the velocity determination is much smaller in the TV catalogue, with errors about 1 km/s. However, all 484 hyperbolic meteors from the database (Figure 3) show similar distributions of heliocentric velocities for sporadic and shower meteors with hyperbolic excesses. The equation $\mathrm{d}a = 2v_H a^2 \mathrm{d}v_H$ shows that, for a large value of the semimajor axis a, even a small error in the velocity determination can change an elliptic orbit to a hyperbolic one.

The uncertainties which result from the measuring errors make it very difficult to discriminate interstellar meteors among the hyperbolic orbits, and even impossible if, in connection with their orbital and geophysical parameters, individual cases are not analyzed in detail. It is impossible to detect a hyperbolic excess of a heliocentric velocity which is of the same order as the error in the velocity measurement. This has to be taken into consideration by those interested in the detection of interstellar particles, and their results should contain reliable information about the velocity determination of those particles. The results concerning the identification of interstellar particles, without a proper error analysis, might need some revision. In most cases, possible interstellar meteoroids can only be found within the error bars of the determined heliocentric velocity, and thus their flux remains unclear.

Other sources which can produce the hyperbolicity of the meteor orbit, such as a planetary perturbation of a meteoroid, the ejection velocity of a meteor particle from the parent body, or collisions of small bodies, are negligible by comparison. Two catalogues of our data were searched for hyperbolic meteors unbound due to a close encounter with one of the major planets.

Analyzing TV meteor orbits from the Japanese catalogue (SonotaCo, 2009), we found only 22 meteoroids from the 7489 hyperbolic orbits had had a close encounter with a planet. However, the backwards integration processes did not show any considerable changes in their orbits. None of the hyperbolic orbits from the catalogue was caused by a meteoroid encountering a planet (Hajduková et al., 2012).

Also, in the photographic catalogues, containing 4581 orbits, no meteors were found whose hyperbolicity was caused by planetary perturbation (Jakubík, 2001). It can be concluded that, in general, the proportion of hyperbolic meteoroids influenced by the planetary perturbation is, from the statistical point of view, minor.

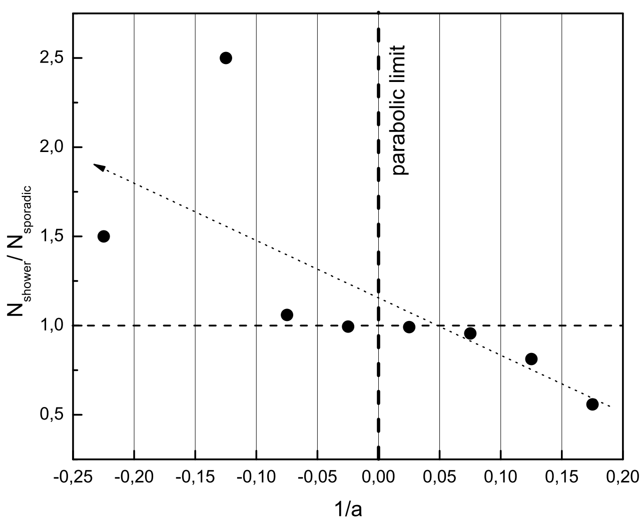

Figure 4 – The proportion of shower meteors within 9 intervals of values of reciprocal semimajor axis $1/a$ close to the parabolic limit and beyond. The number of shower meteors among the orbits of highest hyperbolic excesses exceeds the proportion 1:1 and is clear evidence of errors, in most cases from the velocity determination.

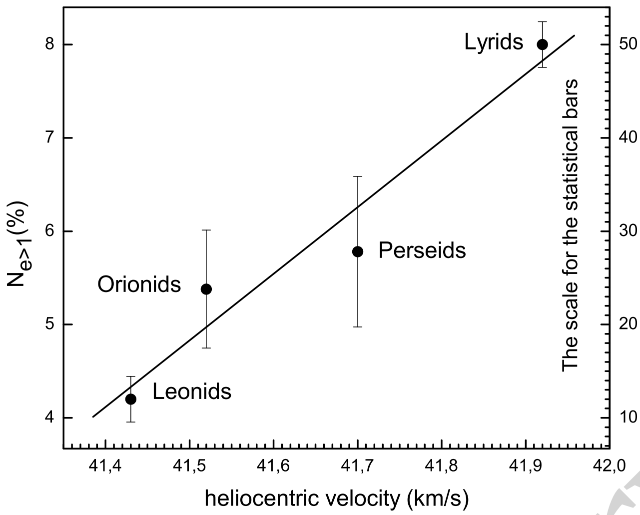

Figure 5 – A dependence of the contribution of hyperbolic meteors in meteor showers on the mean heliocentric velocity of a particular shower ($N_{e>1}/N = f(v_H)$) is evident (Hajduková, 2011). This shows that hyperbolic orbits among shower data are the consequence of error distribution in the velocity.

5 On the frequency of interstellar meteoroids

5.1 Analysis

The first clear evidence of errors (in most cases from the velocity determination) is the concentration of shower meteors among the hyperbolic orbits. To follow the influence of such errors on the sample of orbits determined as hyperbolic, diagrams showing the position of radiants of orbits for the selected intervals of values of $1/a$ close to the hyperbolic limit and beyond were constructed (Hajduková, 1994). We would expect a gradual decrease in the concentration of shower radiants with decreasing values of $1/a$, but actually the opposite was found. Their concentration is higher among the orbits with the highest hyperbolic excesses, reaching the proportion 1:1 in the photographic catalogue. To demonstrate this fact and verify it, we plotted the numbers of the proportion of shower meteor among the hyperbolic orbits for selected intervals of $1/a$, as follows: $0.15 < 1/a < 0.2$, $0.10 < 1/a < 0.15$, $0.05 < 1/a < 0.10$, $0.0 < 1/a < 0.05$, $-0.05 < 1/a < 0.0$, $-0.10 < 1/a < -0.05$, $-0.15 < 1/a < -0.10$, $-0.20 < 1/a < -0.15$, and $-0.25 < 1/a < -0.20$, using the quality selection of the TV catalogue (Figure 4). The ratio of shower meteors to all meteors reaches or exceeds 50% for all intervals of $1/a$ corresponding to hyperbolic orbits. There is also a clear tendency for this ratio to increase (outlined with the dotted arrow) with decreasing values of $1/a$.

The analysis of meteor showers, particularly those with a heliocentric velocity close to the parabolic limit (Perseids, Lyrids, Orionids, and Leonids), showed that the proportion of hyperbolic orbits is different in different meteor showers. A dependence of the contribution of hyperbolic meteors in meteor showers on the mean heliocentric velocity of a particular shower, $N_{e>1}/N = f(v_H)$, was found. This was true for all three databases. Figure 5, constructed using TV data, is taken from the author's 2011 paper (Hajduková, 2011). This dependence is again a clear proof that hyperbolic orbits among shower data result from the error distribution in the velocity determination.

These results and the assumption that shower meteor orbits were determined with the same precision as non-shower meteor orbits, led us to conclude that there is a lack of statistical arguments in favor of the presence of real hyperbolic orbits among the orbits in the catalogues investigated.

Another aspect supporting this position is the abundance of retrograde orbits among hyperbolic meteors. In the TV data set, 6594 out of 7489 hyperbolic orbits (88%) are retrograde. Errors in the measured velocity increase towards higher velocities, which belong mostly to retrograde orbits. Thus, they increase the proportion of hyperbolic orbits among particles moving on retrograde orbits. Among the radar data, the proportion of hyperbolic orbits is approximately 2.5 times higher for retrograde orbits than for prograde orbits. This means that the number of real hyperbolic orbits is also at least 2.5 times less than in the data set of Hajduková and Paulech (2007). Our conclusions are further supported by the fact that the meteor showers with the highest abundance of hyperbolic orbits are precisely those having retrograde orbits, such as the Perseids, Orionids, and Leonids.

Meteors with the largest values of hyperbolic excesses were selected for closer analysis. Taking into account that the distribution of excess velocities of interstellar particles should correspond to the distribution of radial velocities of close stars, we obtain a heliocentric velocity $v_H = 46.6$ km/s of an interstellar meteor arriving at the Earth. In the photographic catalogue, 59 orbits corresponding to this velocity were found, but 54 of them were in catalogues of lower quality. In the most precise orbits from the catalogue of Jacchia and Whipple (1961), the largest value of hyperbolic excess was 0.7 km/s. Similarly, in the TV data, none of the meteors reached the velocity required from the velocity distribution of neighboring stars; the hyperbolic excesses in all cases were about one order less. All special cases with the highest hyperbolic excesses, from all catalogues, were analyzed individually, and an upper limit for the contribution of possible interstellar meteoroids for each database was determined. However, the results did not produce any convincing arguments in favor of their interstellar origin. Moreover, the distribution of the orbital characteristics of interstellar meteoroids is expected to follow the motion of interstellar material; however, the hyperbolic meteors from our databases did not show any similar orbital characteristics. No concentration of their radiants towards the Sun's apex was observed. An overview of the investigated orbits from all catalogues investigated and the results of our analyses are shown in Table 1.

Table 1 – Overview of hyperbolic orbits $N_{e>1}$ from all catalogues investigated (with the number of all orbits $N_{\rm all}$) and results of our analyses: the number of possible interstellar meteoroids $N_{\rm ism}$, proportions of interstellar meteoroids $N_{\rm ism}/N_{\rm all}$ among all meteors in the database, derived flux of them $\Phi_{\rm ism}$, and their proportion among the hyperbolic orbits $N_{\rm ism}/N_{e>1}$.

Technique	Photographic		Radar	Video
Mass (kg)	$> 10^{-4}$		$> 7 \times 10^{-8}$	$> 10^{-5}$
Source	IAU MDC		IAU MDC	TV cat.
	Lindblad 1987	L. et al. 2005	Lindblad 2003	SonotaCo 2009
			Quality selection	Quality selection
$N_{\rm all}$	2910	4581	39 145	14 763
$N_{e>1}$	347	527	970	484
$N_{v_H>46.6}$		59	258	0
$N_{\rm ism}$	15	28	54	<19
$N_{\rm ism}/N_{\rm all}$	0.002	0.006	0.0014	0.0013
$\Phi_{\rm ism}$ ($\rm m^{-2}s^{-1}$)	8×10^{-18}	7×10^{-19}	6×10^{-14}	$< 10^{-16}$
$N_{\rm ism}/N_{e>1}$	0.017	0.053	0.052	0.039

5.2 Proportion and flux of interstellar meteoroids

The analysis of hyperbolic meteor orbits among the photographic meteors of the IAU Meteor Data Center showed that the vast majority of hyperbolic orbits were caused by the dispersion of determined velocities (Hajduková, 1994; 2008). Analyzing meteors from the most precise Harvard catalogues of photographic meteors and comparing them with the other data sets the frequency limit for hyperbolic meteors with excesses corresponding to possible interstellar meteors to 2×10^{-3}. From the updated version of the catalogue, which contains almost double the number of meteor orbits, we determined the proportion of interstellar meteoroids as 6.1×10^{-3}. The analysis of the radar meteors of the IAU MDC also showed that only a fraction of all meteors from the database, 1.4×10^{-3}, could be ascribed as having a possible interstellar origin (Hajduková and Paulech, 2007).

For fluxes of interstellar meteoroids $\Phi_{\rm ism}$, we obtained values of 6×10^{-14} $\rm m^{-2}s^{-1}$ for radar data (with masses $m > 7 \times 10^{-8}$ kg) and 7×10^{-19} $\rm m^{-2}s^{-1}$ for photographic meteors (with masses $m > 10^{-3}$ kg). The values of the fluxes are related to the flux $\Phi_{\rm all}$ given by the Divine model (Divine, 1993) as a proportion of the hyperbolic particles to all observed particles in a particular observation, which is explained in more detail by Hajduková and Hajduk (2006). The same method was used to determine the flux of interstellar meteoroids obtained from the Japanese TV catalogue. The proportion of hyperbolic orbits in these data, containing 64 650 meteors, decreased significantly after selecting only quality orbits, from 11.58% of the total number to 3.28% of the quality selection. After an error analysis, the upper limit of the proportion of possible interstellar meteors to interplanetary ones among all the investigated meteor orbits was determined to be 1.3×10^{-3} (Hajduková, 2011). This proportion of 14 763 meteors from the data set investigated allowed us to determine the value of 10^{-16} $\rm m^{-2}s^{-1}$ for the flux of interstellar meteoroids with a limiting mass of 10^{-5} kg.

6 Summary and conclusions

Accurate velocity measurements are the basis of the search for interstellar particles. The uncertainties which result from the measuring errors make the discrimination of interstellar meteors among the hyperbolic orbits very difficult. In most cases, possible interstellar meteoroids can only be found within the error bars of the determined heliocentric velocity. The resulting hyperbolicity of the determined meteor orbit is more likely due to measurement errors than to the interstellar origin of the particle or other processes which operate in the Solar System.

We briefly summarize the various factors contributing to an unreal hyperbolic population and speaking against the occurrence of interstellar meteoroids among registered meteoroid orbits:

- a high concentration of shower meteors among the hyperbolic orbits;
- an increase in the proportion of shower meteors with decreasing values of $1/a$ close to the parabolic limit and beyond, reaching or exceeding 1:1;
- a dependence of the contribution of hyperbolic meteors in meteor showers on the mean heliocentric velocity of a particular shower;
- a high proportion of hyperbolic orbits among particles moving on retrograde orbits;

- a dependence of the proportion of hyperbolic orbits in the data on the quality of observations and accuracy of measurements;
- the less precise the catalogue, the higher the hyperbolic excesses;
- the hyperbolic meteors did not show any similar orbital characteristics which follow the motion of interstellar material; and
- a concentration of their radiants towards the Sun's apex was not observed.

In summary, we may conclude that, since many apparent hyperbolic orbits are present in the databases investigated, this detailed analysis questions the occurrence of interstellar meteoroids in the vicinity of the Earth, at least in the range of large meteoroid particles corresponding to the detection techniques used. The analysis of three catalogues of meteors showed that the hyperbolicity of the vast majority of meteor orbits in the catalogues investigated is the result of inaccurate velocity determination: 96% to 98% of meteoroids with orbits determined as hyperbolic definitely belong to the Solar System meteoroid population. About half of them are shower meteors and the other half should be assigned to the interplanetary sporadic background.

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References

Baggaley W. J. (1995). "Radar surveys of meteoroid orbits". *Earth, Moon, Planets*, **68**, 127–139.

Baggaley W. J. (1999). "The interstellar particle componant measured by AMOR". In Baggaley W. J. and Porubčan V., editors, *Meteoroids 1998*, Astron. Inst. Slovak Acad. Sci., Bratislava, pages 265–273.

Baggaley W. J., Marsh S. H., and Close S. (2007). "Interstellar meteors". In Wilson A., editor, Proceedings *Workshop on Dust in Planetary Systems*, 26–30 September 2005, Kauai, Hawaii, ESA SP-643, pages 27–32.

Baggaley W. J., Taylor A. D., and Steel D. I. (1993). "The southern hemisphere meteor orbit radar facility: AMOR". In Štohl J. and Williams J. P., editors, *Meteoroids and their Parent Bodies*, Astron. Inst. Slovak Acad. Sci., Bratislava, pages 53–56.

Baguhl M., Grün E., Hamilton D. P., Linkert G., Riemann R., Staubach P., and Zook H. A. (1995). "The flux of interstellar dust observed by Ulysses and Galileo". *Space. Sci. Rev.*, **72**, 471–476.

Divine N. (1993). "Five populations of interplanetary meteoroids". *J. Geophys. Res.*, **98**, 17029–17048.

Grün E. (1993). "Dust detection from space vehicles". In Štohl J. and Williams J. P., editors, *Meteoroids and their Parent Bodies*, Astron. Inst. Slovak Acad. Sci., Bratislava, pages 349–356.

Grün E., Gustafson B. A., Mann I., Baguhl M., Morfill G. E., and Staubach P. (1994). "Interstellar dust in the heliosphere". *Astronomy and Astrophysics*, **286**, 915–924.

Grün E., Landgraf M., Horányi M., Kissel J., Krüger H., Srama R., Svedhem H., and Withnell P. (2000). "Techniques for galactic dust measurements in the heliosphere". *J. Geophysical Research*, **105**, 10403–10410.

Grün E., Staubach P., Baguhl M., Hamilton D. P., Zook H. A., Dermott S., Gustafson B. A., Fechtig H., Kissel J., Linkert D., Srama R., Hanner M. S., Polanskey C., Horanyi M., Lindblad B. A., Mann I., McDonell J. A., Morfill G. E., Schwehm G. (1997). "South-north and radial traverses through the interplanetary dust cloud". *Icarus*, **129**, 270–288.

Hajduk A. (2001). "On the very high velocity meteors". In Warmbein B., editor, *Proceedings of the Meteoroids 2001 Conference*, Kiruna, Sweden, 6–10 August 2001, ESA SP-495, pages 557–559.

Hajduková M., Jr. (1994). "On the frequency of interstellar meteoroids". *Astronomy and Astrophysics*, **288**, 330–334.

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

Hajduková M., Jr. (2011). "Interstellar meteoroids in the Japanese TV catalogue". *Publ. Astron. Soc. Japan*, **632**, 481–487.

Hajduková M., Jr. and Hajduk A. (2006). "Mass distribution of interstellar and interplanetary particles". *Contrib. Astron. Obs. Skalnaté*, **36**, 15–25.

Hajduková M., Jr., Kornoš L., and Tóth J. (2012). *Meteoritics & Planetary Science*, submitted.

Hajduková M., Jr. and Paulech T. (2002). "Interstellar and interplanetary meteoroid flux from updated IAU MDC data". In Warmbein B., editor, *Proceedings of the International Conference on Asteroids, Comets, Meteors 2002* (ACM 2002), Berlin, Germany, 29 July–2 August 2002, ESA SP-500, pages 173–176.

Hajduková M., Jr. and Paulech T. (2007). "Hyperbolic and interstellar meteors in the IAU MDC radar data". *Contrib. Astron. Obs. Skalnaté Pleso*, **37**, 18–30.

Hawkes R. L., Close T., and Woodworth S. C. (1999). "Meteoroids from outside the Solar System". In Baggaley W. J. and Porubčan V., editors, *Meteoroids 1998*, Astron. Inst. Slovak Acad. Sci., Bratislava, pages 257–264.

Hawkes R. L., Woodworth S. C. (1997). "Do some meteorites come from interstellar space?". *J. R. Astron. Soc. Can.*, **91**, 68–73.

Hoffmeister C. (1937). *Die Meteore*. Akademische Verlagsgeselschaft M. B. H., Leipzig.

Jacchia L. G. and Whipple F. L. (1961). "Precision orbits of 413 photographic meteors". *Smithsonian Contr. Astrophys.*, **4**, 97–129.

Jakubík M. (2001). *Extreme Hyperbolic Meteors*. M. Sc. thesis, Comenius University, Bratislava, Slovakia.

Kresák L. (1992). "On the ejection and dispersion velocities of meteor particles". *Contrib. Astron. Obs. Skalnaté Pleso*, **22**, 123–130.

Krüger H., Grün E., Landgraf M., Baguhl M., Dermott S., Fechtig H., Gustafson B. A., Hamilton D. P., Hanner M. S., Horányi M., Kissel J., Lindblad B. A., Linkert G., Mann I., McDonell J. A. M., Morfill G. E., Polanskey C., Schwehm G., Srama R., Zook H. A. (1999). "Three years of Ulysses dust data: 1993–1995". *Planet. Space Sci.*, **47**, 363–383.

Krüger H., Landgraf M., Altobelli N., and Grün E. (2007). "Interstellar dust in the solar system.". *Space Science Reviews*, **130**, 401–408.

Lindblad B. A. (1987). "The IAU Meteor Data Centre in Lund". In Ceplecha Z. and Pecina, P., editors, *Interplanetary Matter*, Proc. 10th European Reg., Meeting of the IAU, Prague, pages 201–204.

Lindblad B. A. (2003). Radar data of IAU MDC. *Private communication.*

Lindblad B. A., Neslušan L., Porubčan V., Svoreň J. (2005). "IAU Meteor Database of photographic orbits version 2003". *Earth, Moon, and Planets*, **93**, 249–260.

Musci R., Weryk R. J., Brown P., Campbell-Brown M. D., and Wiegert P. (2012). "An optical survey for millimeter-sized interstellar meteoroids". *Astrophys. J.*, **745**, 161–166.

Öpik E. (1934). "Results of the Arizona expedition for the study of meteors III. Velocities of meteors observed visually". *Harvard Circ.*, **389**, 1–9.

Taylor A. D., Baggaley W. J., and Steel D. I. (1996). "Discovery of interstellar dust entering the Earth's atmosphere". *Nature*, **380**, 323–325.

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

Vereš P. and Tóth J. (2010). "Analysis of the SonotaCo video meteoroid orbits". *WGN, Journal of the IMO*, **38**, 54–58.

Weryk R. J. and Brown P. (2005). "A search for interstellar meteroids using the Canadian Meteor Orbit Radar (CMOR)". *Earth, Moon, and Planets*, **95**, 221–227.