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Instrumentally documented meteorite falls: two recent cases and statistics from all falls

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Abstract. Precise data from instrumental observations of fireballs, especially those for really bright bolides, provide information about the population and physical properties of meteoroids, i.e. fragments of asteroids and comets, colliding with the Earth's atmosphere. An overview of what is known about meteoroids and their parent bodies from analysis of bolides producing meteorite falls, especially from the instrumentally observed meteorite falls, was a topic of this invited contribution. At present, atmospheric and orbital information with different degree of reliability and precision for these meteorite falls is known for only 24 cases. This topic was described in detail in the review work of Borovička, Spurný and Brown (2015) (Borovička *et al.*, 2015). However, this work contains all instrumentally documented falls until end of 2013. To bring this work up to date, two new instrumentally observed meteorite falls in 2014, the Annama meteorite fall in Russia on 18 April 2014 and the Žďár nad Sázavou meteorite fall in the Czech Republic on 9 December 2014, are presented and commented in this paper. Especially the second case is mentioned in more detail including still unpublished data. Statistical analyses resulting from all 24 instrumentally documented falls are also mentioned.

Keywords. fireball, meteorite fall, meteorite, asteroid

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1. Introduction

Meteorite falls are products of an interaction of larger debris of asteroids and comets with Earth's atmosphere, so their observations can tell us much about their parent bodies. Through fireball observations and subsequent meteorite recoveries we can get direct information about internal composition and basic physical properties of asteroids and comets. We can better understand the processes connected with atmospheric flight of centimeters to meters sized interplanetary bodies. On the basis of these observations and their analyses we can predict and describe much dangerous collisions of much larger bodies which could cause large scale catastrophes. Therefore, every new fireball producing meteorite with precise atmospheric and orbital data gives us invaluable information not only about each particular event but also about its parent body. A detailed inventory of all known instrumentally documented falls is given in the review work Borovička *et al.*, 2015. From the list of all 22 cases (status until end of 2013) it can be seen that meteorites were observed to fall from meteoroids of a wide range of masses, causing fireballs different by orders of magnitude in terms of energy and brightness. At the lower end, there were meteoroids of initial masses of only a few dozens of kg causing fireballs of absolute magnitude of about −10 or even slightly less, such as Bunburra Rockhole (Bland *et al.*, 2009, Spurný *et al.*, 2012) or Mason Gully (Spurný *et al.*, 2011). On the opposite end some meteorite falls were produced by large (>meter-sized) meteoroids associated with superbolide events which occur globally approximately every two weeks (Brown *et al.*, 2002) and only very rarely were reliably documented. The most typical representative cases are Tagish Lake (Brown *et al.*, 2000), Almahata Sitta (Jenniskens *et al.*, 2009) and recently the largest ever observed bolide Chelyabinsk (Borovička *et al.*, 2013, Brown *et al.*, 2013 and Popova *et al.*, 2013). In such cases when good dynamic and photometric data are available we can obtain insight into the internal structure of the pre-atmospheric meteoroid for comparison with the physical structure of asteroids as determined from other kind of observations. In the list of instrumentally documented falls the most exceptional cases are the heterogeneous falls Almahata Sitta (Jenniskens *et al.*, 2009) and Benešov (Spurný *et al.*, 2014), which revolutionized our view of the structure and composition of small asteroids; the Příbram-Neuschwanstein orbital pair (Ceplecha, 1961 and Spurný *et al.*, 2002), new type of meteorites such as the carbonaceous chondrite Tagish Lake (Brown *et al.*, 2000) or anomalous achondrite Bunburra Rockhole (Bland *et al.*, 2009) and the Chelyabinsk fall, which produced a damaging blast wave (Brown *et al.*, 2013 and Popova *et al.*, 2013). Apart from these cases summarized and in detail described in Borovička *et al.*, 2015, there are two new instrumentally documented meteorite falls observed in 2014. They are closely described in the following two sections. In this respect this work could serve as an addendum to the basic review work given in Borovička *et al.*, 2015.

2. The Annama meteorite fall

The first instrumentally documented meteorite fall in 2014 is named Annama after a nearby river which is the closest landmark to the location where meteorites were found. It occurred in the remote territory of the Kola Peninsula in Russia close to Finnish border on 18 April 2014 at $22^h 14^m 9^s$ UT. It was recorded by 3 cameras of the Finnish fireball network and by the one dashboard camera from Russian town Snezhnogorsk. Results concerning bolide trajectory and heliocentric orbit based on analysis of these records were published in Trigo-Rodriguez *et al.*, 2015 and Gritsevich *et al.*, 2014. However from the available data it is evident that the quality of instrumental records as well as the precision and reliability of the published results, especially concerning the trajectory location and velocity determination, is very limited. The main reason is that the Finnish cameras with mediocre resolution were mostly very far from the bolide trajectory (from 220 to 820(!) km) and that the only useful velocity information was available from a dashboard camera placed in a moving car. Moreover, for the calibration of this record only the Google maps application instead of in-situ measurements was used. Although this camera was closer to the bolide than Finnish cameras (from scarce available data it was approximately 200 - 120 km (unfortunately location of the beginning and end of the trajectory is not published yet)) still the positional precision is very limited and cannot be better than about 1 km. It means that for velocity solution it is still worse. Reliable dynamic solution including deceleration information is thus missing. Similarly exact photometric information is missing completely. However from the records which are available also from very large distances (over 700 km - Finnish station Mikkeli) and from several infrasound records from all Scandinavia it is evident that it was a very bright event with at least one big flare which could reach almost a super-bolide category. The published estimate of the maximum absolute brightness is about -18 magnitude (Trigo-Rodriguez *et al.*, 2015). Cascade fragmentation is also visible on the video record. In such cases a large number of pieces can reach the ground and they are spread over quite a large territory especially when the slope of the trajectory is relatively small as in this case (about 34 degrees). Strewn field containing wide range of masses from subgram to several kilograms is thus created. In this aspect the Annama resembles somewhat larger case, the Buzzard Coulee meteorite fall (Hildebrand *et al.*, 2009 and Milley, 2010). Approximate position of the Annama strewn field was determined and its correctness was

Figure 1. Part of the all-sky image of the Žďár bolide from the Czech station Polom.

confirmed by the find of two meteorites with masses 120 and 47.5 grams after a search in the predicted area. They were classified as H5 ordinary chondrites of S2 shock level and W0 weathering grade. Due to a very difficult terrain no other finds were reported. It was determined that the initial meteoroid before its collision with Earth orbited the Sun on a quite common Apollo-type orbit. Generally, it can be concluded that this case belongs to the category of rather crudely described meteorite falls.

3. Žďár nad Sázavou meteorite fall

The second instrumentally documented meteorite fall in 2014, named Žďár nad Sázavou (further Žďár) after a nearby county town where meteorites were found, was observed on 9 December over the Czech Republic. It occurred in the early evening, still during late local twilight on $16^h16^m45^s$ UT over northeastern part of the Czech Republic close to the border with Poland. After 9 seconds long flight it terminated over the Highlands county in the central part of the Czech Republic. At the maximum it reached -15 absolute magnitude and riveted attention of thousands of casual witnesses not only in the Czech Republic but practically in whole Central Europe where it was clear during its passage. Fortunately after several days of cloudy skies, the weather cleared over significant part of the Czech Republic and so this extraordinary bolide could be recorded also by the autonomous cameras of the Czech part of the European fireball network (EN) (Spurný *et al.*, 2007). Readiness of the Czech fireball network (CFN) proved to be crucial for full and detailed description of this event. Practically no other useful optical records of this bolide were taken by any other instrument. This was thus another tangible result of the systematic operation and modernization of the CFN. This network has been modernized several times (Spurný *et al.*, 2007), but the last significant improvement has been realized during the last two years when a high-resolution digital autonomous fireball observatory (DAFO) was developed and gradually installed alongside the older "analog" (using photographic films) autonomous all-sky system (AFO) on all Czech stations during 2014.

Table 1. Atmospheric trajectory data for the Žďár nad Sázavou bolide.

	Beginning	Max. brightness	Terminal
Height (km)	98.121 ± 0.016	37.39	24.726 ± 0.012
Velocity (km/s)	21.94 ± 0.03	19.2	4.70 ± 0.08
Longitude (deg E)	18.00146 ± 0.00012	16.340	15.99087 ± 0.00010
Latitude (deg N)	49.94055 ± 0.00016	49.596	49.51618 ± 0.00016
Slope (deg)	26.08 ± 0.02	24.98	25.07 ± 0.02
Azimuth (deg)	252.79 ± 0.02	251.56	250.60 ± 0.03
Total length (km)		170.60	

Table 2. Radiant and orbital elements (J2000.0) for the Žďár nad Sázavou meteoroid. Time is given for the middle point of the beginning part of recorded trajectory (from beginning to the main flare) which was used for radiant determination.

Time (UT)	$16^h 16^m 49.72^s \pm 0.01^s$
α_R (deg)	65.957 ± 0.006
δ_R (deg)	30.453 ± 0.007
v_∞ (km/s)	21.94 ± 0.03
α_G (deg)	69.313 ± 0.015
δ_G (deg)	26.967 ± 0.015
v_G (km/s)	18.60 ± 0.03
v_H (km/s)	37.14 ± 0.02
a (A.U.)	2.101 ± 0.008
e	0.6806 ± 0.0014
q (A.U.)	0.6709 ± 0.0003
Q (A.U.)	3.530 ± 0.017
ω (deg)	257.75 ± 0.02
Ω (deg)	257.262
i (deg)	2.803 ± 0.014
P (years)	3.044 ± 0.019
TP_J	3.41

Apart from the imaging system, both camera types are equipped with rapid photometers (5000 samples per second) and mechanical (AFO) or electronic (DAFO) shutters with 15, respectively 16 interruptions per second.

The sensitivity limit is −4 magnitude for AFO (about 2−3 mag lower during a full Moon) and −2 magnitude for DAFO (with almost no dependence on lunar phase). Fireball observations made with this new digital autonomous system contain more information especially in the beginning and terminal parts of the luminous trajectory. They are also significantly more efficient, and, when combined with improved analysis techniques, are more precise than results from any previous system. One of its important advantages is the ability to take usable photographic records also during periods when it is not completely dark (twilight periods) and not completely clear. This proved to be crucial because the Žďár bolide occurred during twilight for most of stations and when it was not perfectly clear. Therefore at majority of stations only digital system was in operation and took the most important records. It is symbolic that the last stage of modernization of the Czech fireball network was finished by the installation of the DAFO on the last station just in the afternoon on 9 December 2014 and that this station was the closest to the end of the fireball trajectory where it was clear. This record was the most important

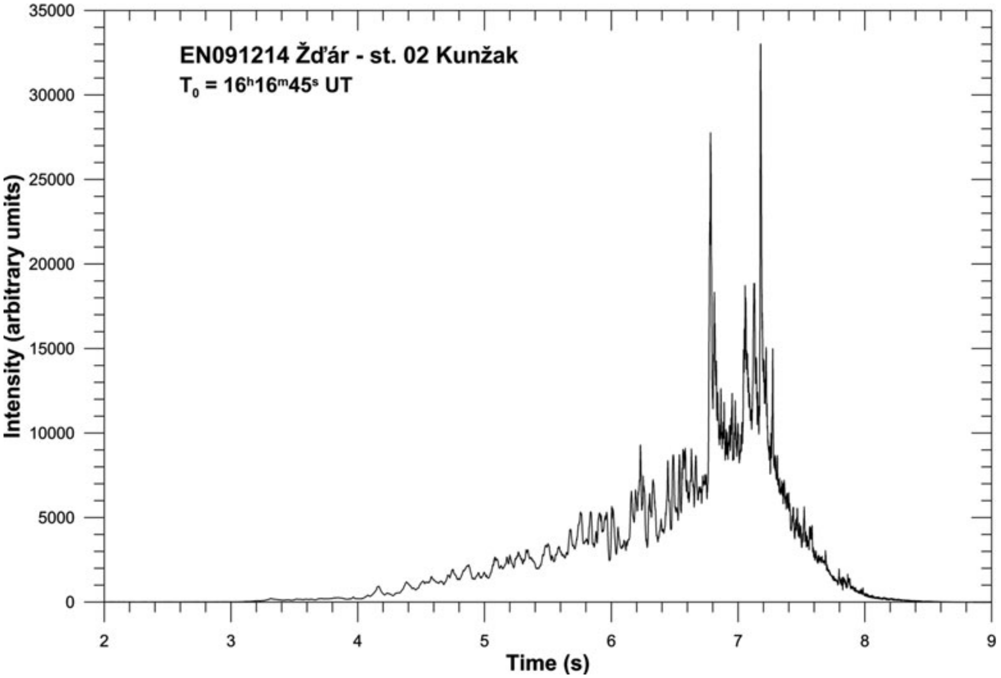

Figure 2. Apparent light curve of the Žďár nad Sázavou bolide (designated as the EN091214 fireball) taken by the fast photometer with 5000 samples/s at the station Kunžak

for the localization of the impact area and determination of the velocity and deceleration near the end of the luminous trajectory.

Altogether, this bolide was photographed by 10 autonomous fireball cameras of the CFN; 7 images were taken by DAFOs and only 3 (the most eastern stations where it was already sufficiently dark) by AFOs. An example of the fireball record taken by DAFO is in Fig. 1 where the part of all-sky image with the Žďár bolide is shown. In addition to the direct imaging all 21 AFOs and DAFOs in the network recorded the light curve of this bolide by their fast photometers (5000 samples/s) because these photometers work also when weather conditions are bad (the example is in the Fig. 2). Apart from this, the closest AFO to the terminal part of the trajectory at the station Svratouch where it was overcast in time of the bolide, recorded strong detonations of the bolide by its microphone which is also part of this complex instrument for fireball observations. Along with these data from our cameras this bolide was recorded also by many seismic stations in Central Europe. Altogether, this bolide became one of the best documented cases in decades long history of the European fireball network, the longest lasting continuously operational fireball network in the world. Thanks to immediate availability of digital images very precise data on atmospheric trajectory, heliocentric orbit and fragmentation history were quickly determined. The bolide started its luminous flight in a height of 98.2 km and after 170.6 km and 9.2 s long flight terminated in a height of 24.7 km. Average slope of the trajectory was 25.6 degrees. Direction of flight of the main piece was slightly changed after the main flare. Initial speed was 21.94 km/s and during its luminous flight this originally about 50 cm and 170 kg meteoroid decelerated to 4.7 km/s. Basic atmospheric trajectory data are collected in Table 1. The meteoroid's heliocentric orbit before its collision with the Earth was a low-inclined (2.8 degree) quite common

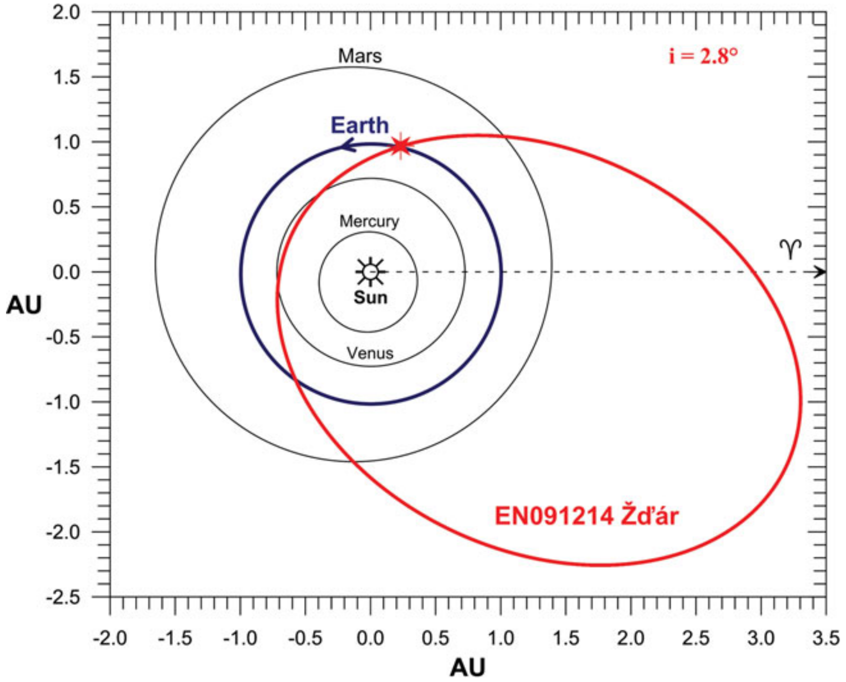

Figure 3. Heliocentric orbit of the Žďár nad Sázavou meteoroid projected onto the plane of the ecliptic along with the orbits of all inner planets and the direction to the vernal equinox.

Apollo-type orbit with a semi-major axis 2.101 AU, perihelion distance 0.671 AU and eccentricity 0.681 (see Table 2 and Fig. 3). This meteoroid thus originated from the central part of the main belt of asteroids.

Based on the first quick analysis it was evident that this event resulted in a multiple meteorite fall. The impact area for possible range of meteorite masses was thus modeled and in a second day, only 18 hours after the fall, we visited the impact area and started systematic searching. It was clear from the beginning that it will be very difficult task because the meteoroid fragmented very high (two largest flares were at altitudes around 40 and 37 km) and in combination with a relatively small slope to the surface the resulting impact area was very long. From smallest 1 gram meteorites to the main 1 kg piece its length was at least 30 km. The low populated area is mostly covered by fields, grasslands and forests. Fortunately it was not yet snow-covered but the situation was highly uncertain. Usually this highlands area is being covered by snow for whole winter period. So it was important to choose very quickly the right strategy for searching. Therefore we focused on the area where more meteorites of searchable sizes could be found and asked for the help of very cooperative groups of amateur astronomers and also some enthusiastic local meteorite hunters. This strategy brought quite a fast result, the first originally 6 g meteorite (after analysis 5.6 g) was found by the amateur astronomer T. Holenda on December 20 just before new snow covered the area. The second meteorite weighting 39.3 g was found by a member of our team (T. Henych) on 12 January 2015 after quick snow melting. This search window lasted only a few days and after that the area was not searchable until mid March. Still third 42 g meteorite was found on 2 May by amateur hunter Z. Tesařík. All three meteorites, which according to the prediction originated in the brightest flare at an altitude of 37 km, were found during dedicated

Figure 4. First two Žďár nad Sázavou meteorites found shortly after the fall (39.3g and 5.6g).

search and all were recovered exactly in the predicted location for given mass (all less than 100 m within the highest probability location). The distance between small 6 g and larger 42 g meteorite was 9.14 km exactly as it was predicted. It nicely illustrates the vastness of the area where meteorites can be found. All meteorites look fresh, only the smallest one is partly broken, remaining two are completely covered by black fusion crust which is highly cracked (see Fig. 4). The meteorites were classified as the L3.9 ordinary chondrites of S2 shock level and W0 weathering grade. It means that it is a very primitive material with high porosity of 15-20% and bulk density of 3.05 g/cm^3. Žďár is then the lowest metamorphosed L chondrite among all known instrumentally documented falls.

All results presented above are still preliminary because not all analyses are finished yet, but certainly they are valid within given standard deviations (as shown in Tables 1 and 2) and very close to the final values, which will be published in an appropriate scientific journal soon. In any case thanks to large number and quality of available instrumental records (photographic, photoelectric, sound and seismic) this case belongs to the best ever described meteorite falls.

4. Statistics resulting from the instrumentally recorded meteorite falls

As it was mentioned above, the complete list of all instrumentally documented falls contains 24 cases (till the date of the IAU Symposium 318). All cases are listed in Table 3 according to the date of a fall. Date corresponds to the UT time of the fireball passage and country corresponds to the territory where meteorites were found. Their world distribution is schematically marked in Fig. 5. The vast majority of these cases (22) is distributed over northern hemisphere, mainly in North America and Europe. Noticeable concentration of these cases in Central Europe is mainly caused by the several decades long effort of the team from the Astronomical Institute of the Czech Academy of Sciences in Ondřejov, which established and continuously coordinates the long-term

Figure 5. World distribution of instrumentally documented meteorite falls (locations marked by circles, valid until end of 2014)

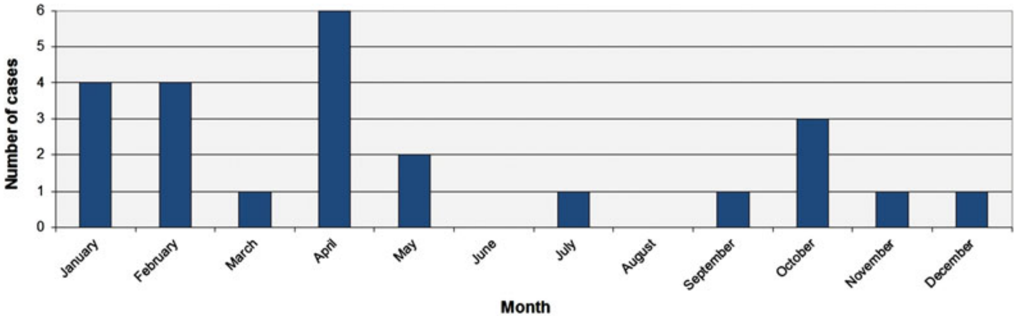

Figure 6. Monthly rates of all 24 instrumentally documented meteorite falls.

systematic observations combined with gradual improvement of analysis methods and techniques (Spurný *et al.*, 2007). The remaining two cases on Southern hemisphere are the result of the activity of the Desert Fireball Network in Australia (Bland *et al.*, 2012, Spurný *et al.*, 2012).

Monthly rates of the instrumentally documented meteorite falls are shown in the Fig. 6. As it was mentioned above, the vast majority of the cases was observed on the northern hemisphere and all these cases belong to the sporadic fireballs. The excess of the meteorite falls in the first half of a year is evident. This annual variation in fireball rates was already explained by Halliday and Griffin (1982) and by Rendtel and Knöfel (1989). They found that meteorite rates are highest near the beginning of spring in either hemisphere and lowest at the beginning of autumn. This is because the antapex reaches the highest declination and is located nearest the zenith in the evening sky. It causes a greater number of slowly moving fireballs and such conditions are directly proportional to the higher probability of possible meteorite falls. This situation well corresponds with the highest observed rate of meteorite falls in April. Note that the reality can differ in individual cases, for example no one Australian fall occurred in autumn months (spring for southern hemisphere), moreover one occurred in April (Mason Gully). On the other hand, all autumn meteorite falls are from the northern hemisphere though the October

Table 3. Instrumentally documented meteorite falls till August 2015

Name	Date (UT)	Country of fall
Příbram	7 April 1959	Czech Republic
Lost City	4 January 1970	USA
Innisfree	6 February 1976	Canada
Benešov	7 May 1991	Czech Republic
Peekskill	9 October 1992	USA
Tagish Lake	18 January 2000	Canada
Morávka	6 May 2000	Czech Republic
Neuschwanstein	6 April 2002	Germany/Austria
Park Forrest	27 March 2003	USA
Villalbeto de la Peña	4 January 2004	Spain
Bunburra Rockhole	20 July 2007	Australia
Almahata Sitta	7 October 2008	Sudan
Buzzard Coulee	21 November 2008	Canada
Maribo	17 January 2009	Denmark
Jesenice	9 April 2009	Slovenia
Grimsby	26 September 2009	Canada
Košice	28 February 2010	Slovakia
Mason Gully	13 April 2010	Australia
Križevci	4 February 2011	Croatia
Sutter's Mill	22 April 2012	USA
Novato	18 October 2012	USA
Chelyabinsk	15 February 2013	Russia
Annama	18 April 2014	Russia
Žďár nad Sázavou	9 December 2014	Czech Republic

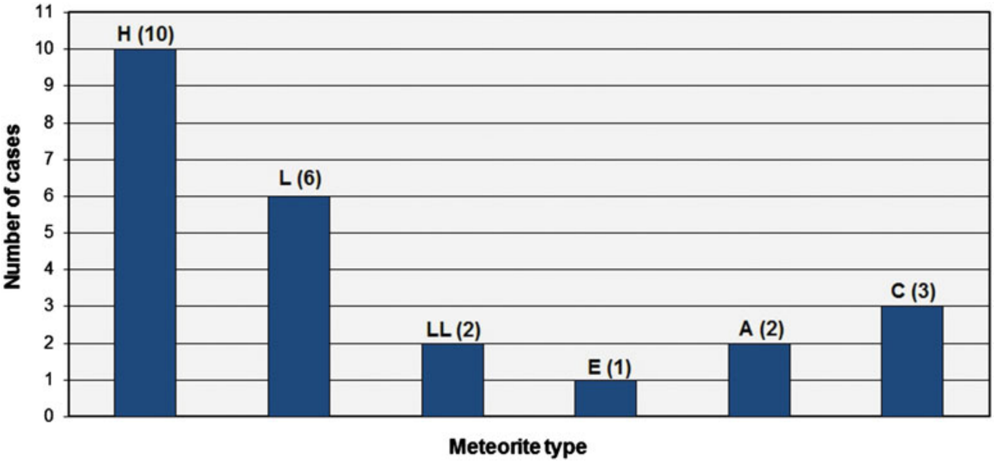

Figure 7. Distribution of individual types of meteorites among all 24 instrumentally documented meteorite falls.

fall Almahata Sitta was from location close to equator where this effect does not play a significant role. In this context it is also useful to mention diurnal distribution of these cases. Again, it also quite well corresponds with the theory, which means that the most suitable daily period is around the early evening when fireballs enter from the Earth's antapex side and have lower speeds. In the list of instrumentally documented falls, there are 12 evening cases in contrast with only 3 morning cases, 4 daylight cases and 5 cases occurred around local midnight.

The last statistical plot (Fig. 7) shows the distribution of individual types of meteorites among all 24 instrumentally documented falls. The most frequent are H chondrites (10) and L chondrites (6). They represent 2/3 of all cases. Other groups such as LL chondrites (2), E - enstatite chondrites (1), A - achondrites (2) and the most fragile group C - carbonaceous chondrites (3) are similarly represented. Note that two cases, Almahata Sitta and Benešov, are very extraordinary because they both contained even more than two meteoritic lithologies and cannot be unambiguously categorized (in Fig. 7 Almahata Sitta is included in achondrites because the prevailing lithology among recovered meteorites is urelite and from the same reason Benešov is included in LL ordinary chondrites).

5. Summary

The main benefit from the very precise description of a meteorite fall is the free delivery of asteroidal (cometary?) material to our laboratories together with the knowledge of all trajectory and orbital parameters. Every new meteorite for which the initial orbit was reliably determined leads to a better understanding of the history, evolution and current conditions of small bodies in our Solar System. Another alternative how to get these extraterrestrial samples into our laboratories is only in spacecraft missions. However to collect such samples is extremely expensive and technically difficult task. The important conclusion from the study of all instrumentally documented meteorite falls is that the meteoroids and it means also their parent bodies, asteroids and comets, are compositionally and structurally much more complicated bodies than it was even recently accepted.

Acknowledgements

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