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Meteor Sky in Time-Domain Astronomy

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Abstract.
Multiwave astronomy provides a means for researchers to see and hear the sky. But that is only part of their perception of the cosmos. The hot handshake of the Universe in the form of a meteor substance burning in the Earth's atmosphere, sometimes with the precipitation of meteorites threatening the environment, occurs every second. A major question that now faces meteor research is how best to organize observations and pursue the tasks of processing existing and new data, in order to obtain information in the time domain of meteor astronomy for solving specific problems. This article discusses the concept of the meteor sky, and the approaches adopted for constructing models of it. It makes use of the data base of meteors of Kharkiv National University of Radio Electronics.

Keywords. Meteor, meteoroid, meteor sky, radiant, database, orbit, radar, interstellar object

1. Introduction

Multiwave astronomy enables researchers to both see and hear the sky. But this is only part of our perception of the cosmos. The hot handshake of the universe in the form of a meteor substance burning in the Earth's atmosphere, sometimes with the precipitation of meteorites threatening the environment, occurs every second. A major question now facing research into meteors is how best to organize observations, and the processing existing and new data, in order to obtain answers in the time domain of meteor astronomy for solving specific problems. One complication is the fact that the meteor sky in the time-domain will differ, depending on the purposes and tasks of the fundamental or applied research in question, as shown in Fig. 1. One of the variables of the meteor sky is the distribution of meteoric radiants in the equatorial coordinate system, together with the geocentric velocity of the meteoroid and the magnitude of the corresponding radiant. The celestial coordinates of the meteor radiant, the velocity, and the time of observation determine the heliocentric orbit of the meteoroid.

This presentation develops the concept of the meteor sky. The objectives are to build meteor sky maps (also in the time-domain) for fundamental and applied problems, based on an archived data base of meteoroid orbits, using information technology and other methods. To that end we define three steps:

Step 1. Perform specific research of a sample of 159320 sporadic orbits from the meteor data base of the Kharkiv National University of Radio Electronics (NURE MBD). NURE contains ~250,000 meteor orbits obtained by classical meteor radar with MARS (Meteor Automated Radar System) between 1972 and 1978.

Step 2. Select meteor parameters, e.g., as in the Table, and models of the meteor sky.

Step 3. Visualization of the distribution of meteor orbits in a system of celestial coordinates (models in the plane), using the software products "Meteor Map" (Golovashchenko & Kolomiyets 2017), as in Fig. 2b, and STATISTICA (Figs. 2a, 2c, 2d).

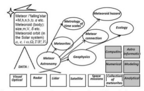

Figure 1. Illustrating the range and type of proposals and demands for meteor information.

2. Data and results

The NURE MBD was used as a tool for studying the meteor sky and also as the basis for its construction. Table 1 lists some of the entries from the NURE MBD meteoroids and objects of the Solar system, and their characteristics.

Table 1 demonstrates the idea of possible limits ("altitudes") of the meteor sky, depending on the remoteness of the aphelion of an orbits from the Sun. The concept gives the values of orbital parameters into which the meteor sky can be divided up according to inclination, eccentricity and aphelion distance, or combinations of them. For objects with hyperbolic orbits (H-objects) and therefore lacking an aphelion distance, the size of the orbit can be estimated indirectly: by examining the intersection of the orbit with the

Table 1. The NURE MBD meteoroids and celestial objects, and some of their characteristics

N	Object	Epoch	δ^o	α^o	Vh, km/s	e	q, AU	a, AU	i^o	ω^o	Ω^o	**Q** AU	$R_{V,N}$ AU
1	H-Meteoroid V_g 31km/s	Apr 16 1977 09^h46^m	+67	274	42.9 for 1 AU	1.08	1.00	-13.0	46	177	26		9.1 1.2
2	H-Meteoroid V_g 69km/s	Sep 10 1978 08^h10^m	+74	19	60 for 1 AU	3.03	0.98	-0.48	96	195	167		1.0
3	H-Asteroid 1I/2017U1 'Oumuamua	Nov 2 2017	+39 +25	279 358	49.7 for 1 AU	1.199	0.26	-1.28	123	242	25		1.4 0.3
4	Meteoroid V_g 70km/s	Feb 12 1973 06^h24^m	-0.3	222	42.4 for 1 AU	0.99	0.84	527	152	222	323	1054	
5	TNO-Sedna	Jan 13 2016			1.04 506 AU	0.85	0.76	507	12	311	144	936	
6	TNO-Eris	dec 9 2014			3.4 for 68 AU	0.44	38	58	44	151	36	98	
7	Main-belt 1 Ceres	Jan 13 2014			17.9 2.68 AU	0.08	2.55	2.8	11	3	80	2.98	

plane of the ecliptic, the radius vector of one of the nodes of the orbit in the presence of two nodes can be used, (e.g., Kolomiyets & Kashcheyev). One of the nodes of the orbit of a meteoroid is always the point of intersection between it and the Earth, i.e., ~1 AU.

To determine the direction of arrival or departure of the interstellar object in the Solar system, it is possible to use the coordinates of the asymptotes of the hyperbolic orbit. Construction of meteoric charts and graphs on a plane in a non-spherical format (rectangular or square), e.g., Fig. 2a, 2c, 2d, was carried out using the STATISTICA program (Borovikov & Borovikov 1997). In Fig. 2b the sky has been visualized using the "Meteoric Map" programme (Golovashchenko & Kolomiyets 2017), the Microsoft Visual Studio 2013 development environment, Windows Forms, the .NET Framework 4.5 platform, the C# language. Features of meteor distributions in the Galactic coordinate system were taken into account (Kolomiyets16a, Kolomiyets 2018).

The conditions for such research were confirmed by deriving satisfactory statistics of the meteor orbits of the NURE database: 100,341 orbits with $0.5 < e < 1.0$, i.e. 62.98% of the total number of sporadic orbits, and 102,946 orbits with $e > 0.5$ (i.e., 64.6% of all sporadic orbits). The relatively high statistics of retrograde orbits (53,178, or 33%) and direct orbits (106,142, or 67%) out of the total of 159,320 investigated are also favorable for research. Fig.2 for the meteor sky in $(\alpha, \delta)^o$ demonstrates the behavior of two meteoroid samples, one with direct and one with retrograde motion. Only the 14,699 retrograde orbits (i.e., having $i > 90$; 9.2% of the total) are presented in Fig.2a and b. For those whose aphelia are located in space between the Earth–Ceres orbits, and the main contributors to the complex of near-Earth asteroids, the Ceres parameters are given in Table 1, line 7 (Wikipedia 2018). Direct orbits in that set include 29,751 (67% of the sample; 18.7% of the total). For the retrograde orbits, the distribution of radiants along the ecliptic is more pronounced. Of the 50,000 meteorites found on Earth to date, 99.8% are believed to have originated in the asteroid belt (Wikipedia 2018, Brown et al. 2013).

What about the more remote areas of the Solar system? There were 14,077 meteoroids with aphelia between 5–50 AU (8.8% of the total), including 2,263 retrograde orbits (16.1% of the sample; 1.4% of the total), and 11,814 direct orbits (83.9% of the sample; 7.4% of the total). 453 meteoroids had aphelia larger than 50 AU (0.3% of the total number), of which 118 were retrograde (26% of the sample; 0.07% of the total), and 335 were direct (74% of the sample; 0.2% of the total).

It was found that the aphelia of the 159,320 meteor orbits of the NURE database investigated could reach values of 2,000 AU (Kolomiyets & Voloshchuk 2015). If so, then the meteor sky above the Earth extends to very large distances from the Sun, the order of those distances being comparable to the remoteness of the first fronts of the Oort cloud from the Sun. Yet that is not the limit of the terrestrial meteor sky. The distribution of the 2,606 radiants of both direct and retrograde hyperbolic orbits (1.6% of the total number) which may be interstellar (part of the hyperbolic orbits may be formed in the Solar system itself) was also investigated. Of those, 731 orbits (28% of the sample; 0.5% of the total) have $i > 90$. Fig.2c shows the combined distribution (direct plus retrograde orbits) of 2,606 meteoroids. Fig.2d shows the distribution of the radiants of 1,875 direct hyperbolic orbits (72% of the sample and 1.1% of the total). Both distributions of the hyperbolic orbits recorded on Earth (Fig.2c, d) indicate a concentration to two regions of the meteor sky $(\alpha, \delta)^o$, one of which includes the coordinates of the apex of the Sun's motion in interstellar space (~270°, ~30°).

The meteor sky of sporadic and stream components also has its distinctions. For example, there is a division of meteors according to their connections with the parent bodies (comets and asteroids). It is therefore possible to design a meteoric sky of *either* cometary *or* asteroid origin.

The NURE MBD electronic data base and archive contains a catalogue of radiants, velocities and orbits in digital format based on the results of radar observations of meteors made near Kharkiv (49°.4 N, 36°.9 E) in 1972–1978 with one of the world's most powerful megawatt pulse radars (MARS: Meteoric Automated Radar System). Working at 31.1 MHz, it enabled the recording of meteors down to +12 mag (Kashcheyev & Tkachuk 1980, Kolomiyets 2012, Kolomiyets 2014). Meteors of such magnitude are called weak, and are produced in the Earth's atmosphere by meteoroids with masses of 10^{-3}–10^{-6} gm invading from space. In the development of that work, conclusions were drawn based on the results of radar observations of meteors down to +8 mag near the equator during the African expedition to Somalia in Mogadishu (2° N, 45° E) in 1968–1970. Observations in Africa were conducted with a special meteoric radar observing system called *Tropic*, working at 36.7 MHz. 6000 orbits from the African expedition have been published (Catalogue 1977). Conclusions were drawn about the properties of sporadic and flux meteors according to the NURE MBD data base (Voloshchuk, Kashcheyev & Kruchinenko 1989, Voloshchuk & Gorelov 2011). NURE also includes a knowledge base (publications, reports, data on paper and data on film, etc.) about the meteor research of 1957–2017; it is partly reflected in the ElAr website (ElAr 2017).

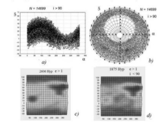

Figure 2. The meteor sky $(\alpha, \delta)^o$ of meteoroids whose orbital aphelia are located in space between the orbits of the Earth and Ceres, $i > 90$ (a and b from Golovashchenko & Kolomiyets 2017, c and d for hyperbolic orbits (c: $0 < i < 180$, d: $i < 90$)

3. Discussion

Traditional ground-based observational radar facilities record meteor phenomena in the Earth's atmosphere within the altitude range from the Earth's surface of 70–130 km (with a maximum at 105 km for radar systems such as MARS). Where do meteors come from? What is the altitude of the meteor sky? How many kinds of meteor skies are there? What is the difference between the observed sky and the true one? What is the relationship between meteors, comets and asteroids, and with other bodies of the

Solar system and objects of the Universe? How are the orbits of meteoroids related to the meteor sky? What is a meteor sky and how can it be visualized? What distances in the solar system are relevant to a meteor sky? What are the dimensions of the solar system? And how do all these aspects change, and how are they related in time?

Answers to these questions should be included in the concept of a meteor sky. In this connection, the distances (in AU) of the eight major planets from the Sun are interesting: 0.38 for Mercury, 0.72 for Venus, 1.0 for Earth, 1.5 for Mars, 5.2 for Jupiter, 9.54 for Saturn, 9.22 for Uranus, and 30.06 for Neptune. The main belt of asteroids (2–3.8 AU) contains a dwarf planet (Ceres, 2.68 AU). The dwarf planet Pluto is characterized by a distance of 39.5 AU. Objects in the region beyond Neptune are called Trans-Neptunian, and include the Kuiper belt, which stretches to 55 AU. Then comes the so-called scattered disk, in which objects such as Eris are found up to a distance of 100 AU. The Oort cloud is found between ~ 50,000–100,000 AU; it can define the outer boundary of the solar system. It is also necessary to take into account the specific distances such as 73, 85 and 95 AU (terminal shock), 135 AU (the heliopause), and 230 AU, (low shock; inhibition of interstellar matter), which are associated with the solar wind and the heliosphere. The closest star system to us is α Centauri, located at a distance of 4.36 light years (i.e., between 100,000 and 1000,000 AU). The interstellar asteroid 'Oumuamua, discovered in 2017 (Meech et al. 2017), is believed to have come from Vega (α Lyr) (RA $18^h\ 36^m\ 56^s.3$, Dec. $+38^\circ\ 47'\ 01''$, located at a distance of 25 light years. So where is the final limit of the meteor sky? Is there such a limit at all?

One of the discoverers of the interstellar object 'Oumuamua was Dr R. Weryk (Meech et al. 2017), who had previously searched for interstellar meteors with the Canadian Orbital Meteor Radar (Weryk & Brown 2005). However, interstellar meteors are still not fully confirmed by scientific facts (e.g., Baggaley 2000, Hajduk 2001). Hyperbolic orbits for comets discovered before 'Oumuamua have also not been fully proven by scientific facts (Hughes 1991). The problem of interstellar meteors is the same as that facing the accuracy of hyperbolic meteor orbits (e.g.,Stohl 1970, Kolomiyets 2015). However, when using search programmes for surveys such as Pan-STARRS, the Southern African Large Telescope (SALT) and programmes of the next generation, e.g., the Extremely Large Telescope (ELT) in Chile (Gangler 2017), scientists expect to find interstellar objects such as 'Oumuamua that are more fully validated scientifically. It has been calculated that interstellar objects like 'Oumuamua pass through the Earth's orbit several times a year, but are too weak and thus too difficult to detect so far (Meech et al. 2017).

There are also other forms of inflow of interstellar material (Vsekhsvyatskiy). It can be assumed that the chances of finding such objects will be increased if all the available meteor data for hyperbolic orbits are reconsidered (e.g., Baggaley 2000, Weryk & Brown 2005, Hajdukova 2008, Hajdukova 2013, Kolomiyets & Kashcheyev, Meisel, Janches & Mathews 2002, etc.) together with theoretical arguments (e.g., Kazantsev 1998, Wiegert 2011) about the positions in the sky and the times at which it is best to watch in order to record interstellar objects. There is a set of observational methods that can be combined under specific observational programmes to research the horizons of the meteor sky. They include (1) modern operational meteor radar systems (e.g., Janches et al. 2015), (2) radars for other purposes and adapted for meteor observations (e.g., Pellinen-Wannberg 2001), and (3) multiple optical meteor networks.

The inclusion in such programmes of sections for new radio systems such as LOFAR (The Low-Frequency Array Radio telescope), SKA (The Square Kilometre Array, GURT (The Giant Ukrainian Radio Telescope) and others is desirable. For the final identification of the interstellar (or other) nature of meteoroids, in addition to their orbital paths, a spectroscopic description is needed. Space missions play an important role in expanding

the horizons of the terrestrial meteor sky. Figs. 2c and 2d illustrate the sections of the meteor sky that may be responsible for the inflow into the Earth's atmosphere of material with orbits of hyperbolic type. At the same time, the daily and annual variations in the number of meteor radiants continue, narrowing or widening the perspective of the surveyed sky depending on the meteoroid's velocity.

In conclusion with regard to the meteor sky, a real assessment of the reliability of events is always necessary, especially with respect to the reality of the concentrations reported from some regions, including the possible concentrations of hyperbolic orbits. Questions regarding the dependence of the meteor sky on the time of day, year, and other conditions have been solved and have been used in Kharkiv (among others) by introducing weighting factors, although there are other methods to employ. These issues will continue to be developed in the future.

To sum up, we add a slightly paraphrased conclusion of specialists concerning 'Oumuamua (Meech et al. 2017), expanding it to the meteor sky and radiant points associated with tiny meteoroids. The history of 'Oumuamua with its space odyssey (and speculated birth date of 600,000 years ago) paints a very different picture of the Galaxy than we could have imagined, when early humans saw a sky in which the stars seemed totally unconnected, and quite unrelated to any small bodies of the solar system (or from meteoroids in the Earth's atmosphere).

Nowadays it is necessary to look even deeper into the Universe, and further back in time, in order to understand the connectivity between the early Universe, small solar-system bodies and the terrestrial meteor sky. Although our Milky Way is ~10^9 years old and contains ~200×10^9 stars, when we observe visitors from space such as 'Oumuamua we begin to appreciate that "perhaps the Universe is still a small place" (Meech et al. 2017). Meteor researchers share with other astronomers the question: "How should we organize the observing and processing of data on meteors and other celestial objects in order to improve our understanding of the astronomical time domain?"

4. Conclusion

The meteor sky is many-sided, depending on the requests. Astronomical information is the cornerstone for answering most queries. The meteor astronomical sky itself is also many-sided. In astronomy, the observational information aout meteors that is associated with the celestial sphere and with the observer at its center is specific. The initial definition of a meteor as a "falling" star reflects symbolically the transient dynamical processes of the meteor sky.

We developed the concept of the altitude of a meteor sky as being dependent upon the aphelion distances of the orbits of meteoroids. The concept was tested on the 159,320 observational data from the NURE MBD. In the course of research into the "altitude" of the meteor sky, its temporal dymamics and the prospects for its study, the following factors could be established.

The aphelion distances of meteoroids orbits taken from the Kharkiv NURE meteor data base have values between 1 and 2,000 AU if e<1 (453 have aphelia larger than 50 AU, i.e., 0.3% of the total).

Meteor matter contains key information about the formation and development of planetary systems and, maybe of the Universe. Meteoroid orbits in the near-Earth space have become an important tool for exploring asteroid or comet hazards. A small fraction (~1%) of observed meteoroids move in hyperbolc orbits. If those hyperbolic orbits are real, then the altitde of meteor sky extends to the stars. The reality of the small interstellar body 'Oumuamua, registered in October 2017, is a weighty argment in favour of raising and

reviewing once again all available meteor data concerning hyperbolic orbits and the theoretical justification regarding where and when it is necessary to watch for them in order to register such objects. Modern observational systems intended for deep space research need to be adaopted to meteor research, as well as maintaining classical methods for programmes of meteor observing, and to expand spectroscopic studies. The horizons of the meteor sky belong to the horizons of time-domain astronomy.

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