```
  SHUTTEROPENTIME       0.500
  CATALOGEQUINOX J2000.0
  BEGIN REFEXPOSURE
   NAME short exposure 2018-09-07 02:20:47
   DATE/YMD         2018           9           7
   TIME/HMS            2          20          47.00
   TABLE STARPOSITION
   "Gam Per"  46.1991666667  53.5063888889   0.0000   -0.0050  122.5968183360   126.6321596970
   "Alf Aur"  79.1725000000  45.9980555556   0.0070   -0.4250   87.6086168505   126.9062348170
   "Zet Cep"  332.7137500000 58.2011111111   0.0020    0.0040  176.1202041270    96.3262832631
   "Alf Cyg " 310.3579166670 45.2802777778   0.0000    0.0020  202.4967859000    87.8043858152
   END TABLE
  END REFEXPOSURE
BEGIN STELPHOTOMETRY
   METHOD aperture
   EXPOSURELENGTH      34.900
   BEGIN PHOTOSTAR
    NAME         Gam Per
    MAGNITUDE/V     2.930
    COLORINDEX/B-V  0.700
    LOCATION.XY           122.596818336       126.632159697
    SIGNAL                55220.67
   END PHOTOSTAR
   BEGIN PHOTOSTAR
    NAME         Alf Aur
    MAGNITUDE/V     0.080
    COLORINDEX/B-V  0.800
    LOCATION.XY           87.6086168505        126.906234817
    SIGNAL                584404.34
   END PHOTOSTAR
   BEGIN PHOTOSTAR
    NAME         Zet Cep
    MAGNITUDE/V     3.350
    COLORINDEX/B-V  1.570
    LOCATION.XY           176.120204127        96.3262832631
    SIGNAL                29652.53
   END PHOTOSTAR
  END   STELPHOTOMETRY
  BEGIN METEOR
   CODE  EN070918_022102
   BEGINNING.XY  101.345998478         76.1782274273
   END.XY         84.6424749193        59.3271419661
   TABLE POSITION.XY
       100.990398483           75.7863417189
       96.1450461751           70.7934275082
       92.3253700420           66.9253704235
       88.0726843916           62.7379990578
       84.9206653913           59.7020943415
   END TABLE
   BREAKPOSITIONS FRONT
   BEGIN SHUTTERBREAK
    NUMBER        5.00
    BREAK.XY         98.4884985209     73.1247846161
    SIGNAL                2239.41
    SIGNAL-ERROR          866.89
   END   SHUTTERBREAK
   BEGIN SHUTTERBREAK
    NUMBER        6.00
    BREAK.XY         97.7246842466      72.3174274853
    SIGNAL                2464.63
    SIGNAL-ERROR          574.43
```

```
    END   SHUTTERBREAK
    BEGIN SHUTTERBREAK
     NUMBER       7.00
     BREAK.XY         96.8828556878      71.5336560685
     SIGNAL               4781.82
     SIGNAL-ERROR         2021.83
    END   SHUTTERBREAK
    BEGIN SHUTTERBREAK
     NUMBER         15.00
     BREAK.XY         90.6707414954      65.2707418769
     SIGNAL                  38570.51
     SIGNAL-ERROR            3090.72
    END   SHUTTERBREAK
    BEGIN ABSOLUTETIME
     BREAK          15.00
     DATE/YMD        2018           9           7
     TIME/HMS           2          21          3.09375
    END ABSOLUTETIME
   END METEOR
  END CAMERA
 END STATION
```

9 Concluding remarks

The format for meteor observational data currently used at the Ondřejov Observatory was introduced. For better understanding, various levels of meteor data were defined. The MED data format is primarily used for Level 1 or Level 2 data. The keywords explained in this article do not represent an exhaustive list. First, there are some alternative keywords, such as POSITION.X and POSITION.Y, which can be used instead of POSITION.XY. Second, there are other keywords for data from radiometers or for calibration of casual video records. Nevertheless, the keywords and environments explained here are the most universal and should be sufficient for typical photographic or video observations of meteors. They can therefore serve for exchange of data or as an inspiration for other projects. In contrast to the recently introduced Global Fireball Exchange format (Rowe 2021), which contains Level 2 data, all original measurements are included in the MED format. The astrometric and photometric calibration can be therefore checked and corrected, if necessary.

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Search for Interstellar Meteoroids with the DIMS Experiment

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One of the objectives of the DIMS (Dark matter and Interstellar Meteoroid Study) optical experiment is the search for interstellar meteoroids. Orbits of meteoroids are obtained from double station meteor observations using wide-field and high-sensitivity cameras deployed in Utah, USA, and Japan. For meteoroids with speeds close to the parabolic limit, any small measurement error can create an artificial hyperbolic orbit. Thus, we evaluate the methods used for the estimation of meteor position and velocity and attempt to reach the required accuracy in the reduced meteor parameters, which is < 1 deg in the radiant position and 0.1 km/s in speed. In this contribution, we present the first results about the data analysis of one of the observation sessions of DIMS carried out in August 2019 from the Telescope Array Site in Utah.

1 Introduction

In addition to meteors coming from the Solar System, fast- and straight-moving luminous events of exotic origin could theoretically be observed in the Earth's atmosphere at night. In our last contribution to IMC 2021 (Barghini et al., 2021), we discussed the phenomenology of the interaction in the atmosphere of macrocopic strange quark matter nuggets, named nuclearites, that were hypothesized in 1984 (De Rujula & Glashow, 1984; Witten, 1984) as possible candidates for macroscopic dark matter. If they exist, their light emission within the atmosphere should be distinguishable from meteors thanks to their peculiar characteristics such as very low altitude and very high speed.

The DIMS (Dark matter and Interstellar Meteoroid Study) project was born in 2017 to develop an experiment that can detect such fast-moving events, by observing the night sky with wide-field and high-sensitivity CMOS cameras (Abe et al., 2022; Kajino et al., 2019, 2017). In this contribution, we discuss the potentiality on DIMS for the detection of interstellar meteors and present first results about the analysis of one of the test sessions of DIMS carried out with two cameras in August 2019 from the Telescope Array (TA) site, an ultra-high energy cosmic ray observatory in Utah (Kawai et al., 2008).

Figure 1 – A picture of one DIMS camera module.

2 Interstellar meteors

Due to the relative motion of our Solar System within the Local Interstellar Cloud (LIC), an inflow of interstellar material to the Earth's position is expected. Nonetheless, the proportion between flux density of local and interstellar objects, as a function of their mass, is still not clear. Up to now, the only reliable observations of interstellar matter flux come from dust measurement from spacecraft (Krüger et al., 2015; Sterken et al., 2015; Strub et al., 2015) and the two recently-observed large interstellar objects (Guzik et al., 2020; Meech et al., 2017). Unfortunately, the analysis of observations of meteors in the Earth's atmosphere is prone to generate a spurious population of hyperbolic orbits. This is due to the measurement errors which are often underestimated for the pre-atmospheric speed and radiant coordinates (Hajduková et al., 2019, 2020). As a matter of fact, the flux of interstellar meteoroids in the Solar System is poorly known, showing a gap for particle masses corresponding to optical meteor observations, due to these issues.

3 Preliminary results of DIMS

The DIMS project is deploying multiple high-sensitivity and wide field of view camera modules to observe fast-moving events that might occur in the lower atmosphere. Each module consists of a Canon ME20F-SH camera, a computer to operate the camera and a solar power supply and environmental control system (Shinto et al., 2022). A photo of a DIMS system is presented in Figure 1. The camera is equipped with Canon EF 35 mm f/1.4L lenses and a 1920 × 1080 pixels CMOS sensor that can operate at 30 or 60 Hz. Cameras are positioned at a distance of 10 – 30 km, being optimal to triangulate events that are expected below 40 km altitude, like nuclearites. Meteors occurs at a higher altitude (typically within 70 – 130 km) and are therefore observed with a lower but still sufficient parallax.

Since 2017, DIMS carried out several observation campaigns mainly in Japan and USA. We present here the analysis of one observation session of the night of the September 1, 2019 with two cameras installed at 17 km distance at the TA site and pointing towards Polaris (Barghini et al., 2021). Figure 2 presents the distribution of geocentric speed and radiant elongation[1] for the 422 meteors detected in that night. The red solid line represent the parabolic limit, *i.e.*, the limit for meteors unbounded with respect to the Solar System. Black points (on the left of the parabolic limit) represent elliptical orbits, whereas red points (on the right) result to be hyperbolic. The fraction of hyperbolic orbits is 8.8%, which is in line with other optical surveys (Hajduková et al., 2020). A dedicated inspection of such events showed that some problems occurred in the automatic reduction pipeline (typically, very short events with bad triangulation outcome). This shows that, to be able to claim possible interstellar meteor candidates, a detailed error analysis must be carried out that accounts for both random and systematic components.

4 Conclusions

At present time, we do not comply to required precision in the reduced meteor parameters, which is < 1 deg in the radiant position and 0.1 km/s in speed. Efforts in the near future will be dedicated to improve the data analysis pipeline trying to accomplish these requirements. During 2021 and 2022, DIMS deployed 3 cameras in Japan (at Kiso Obs., Shinshu Univ. and Akeno Obs.) and 2 cameras in Utah, USA at the TA site. These instruments, operating in automatic acquisition mode, will provide a very large database of meteor observations in next years.

[1] Angle between the meteor geocentric speed and the Earth's revolution speed vectors.

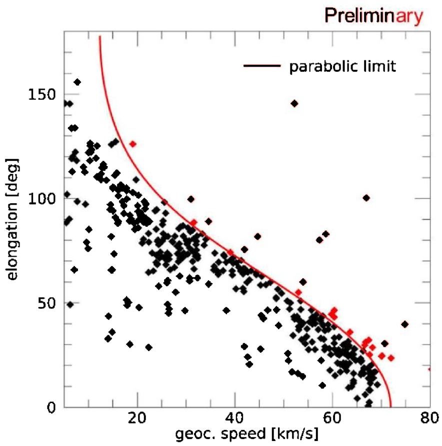

Figure 2 – Distribution of geocentric speed and radiant position (elongation) from a preliminary analysis about pre-atmospheric orbits for the 422 events recorded on the night of September 1, 2019 by two DIMS cameras installed at the TA site (Utah). The red solid line represent the parabolic limit, and the red points represent hyperbolic orbits, almost probably originating from measurement errors.

Acknowledgements

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Dynamical pathways of meteoroids and meteorites

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The aim of the work was to numerically integrate orbits of meteorites with known heliocentric orbit (also called pedigree meteorites) to study their time evolution, stability, and potential source regions. We have used the open-source N-body integrator package REBOUND for the simulations. We have performed simulations for 40 pedigree meteorites, each represented by 100 massless test particles for 100,000 years backward in time. One of the test particles was initially on the nominal orbit, whereas the other 99 particles used slightly different orbits within the error of the nominal orbital elements. We found the 3:1 mean motion resonance with Jupiter and the ν_6 secular resonance as the most common source regions. Using orbital similarity criteria, we have found possible parent bodies for a number of the meteorites, which are subjects of further study.

1 Introduction

Earth's atmosphere is bombarded daily by many tons of interplanetary material in the form of meteoroids, causing meteors. Most of these particles burn up in the atmosphere before hitting the ground.

On the other hand, there are more than 70,000 catalogued meteorites that survived the flight through the atmosphere[1]. However, the meteorites we have been interested in form only a tiny fraction of that value. They are meteorites with known heliocentric orbits, also known as pedigree meteorites. As of October 2022, only 42 pedigree meteorites with published orbits were known[2]. The heliocentric orbits allow us to learn about the meteoroids' dynamical histories in the Solar System.

2 Goals

The aim of this work was to numerically integrate the orbits of 40 meteorites known at the time. We studied the stability and time evolution of their orbital elements, namely the semi-major axis a, eccentricity e, and inclination i. We also determined their potential source regions based on the time evolution.

In addition to the simulations, we have used the D_{SH} (Southworth & Hawkins, 1963) and the D_X (Rudawska et al., 2015) criteria and also the databases of near-Earth asteroids and meteor showers to find potential origin of the studied meteorites based on the orbital similarities.

3 Methods

For the simulations, we have used the REBOUND software package (Rein & Liu, 2012) where we selected the 15th-order non-symplectic integrator IAS15 with adaptive timestep (Rein & Spiegel, 2015).

We have performed simulations for the 40 pedigree meteorites, each with 100 massless test particles. One of the particles used nominal orbital elements, whereas the orbital elements of the rest of the particles were generated using the normal distribution within the error of the orbital elements by fixing the nominal perihelion distance. These particles were numerically integrated for 100,000 years into the past. The simulation took into account 14 massive objects, Sun, the planets, Moon, and four largest asteroids, inspired by (Borovička et al., 2013).

First, we had to find the true anomaly f for each meteorite at the time of the collision with the Earth. Then we integrated the nominal particle back in time with massless Earth and Moon to find the Solar System configuration when the meteoroid was at a distance of 3 Hill radii from Earth. The full simulation started with this new configuration.

In the pictures, we may see examples of the time evolutions for the Novo Mesto meteorite. Figure 1 shows the evolution of the semi-major axis, Figure 2 shows the eccentricity, and Figure 3 shows the evolution of the inclination.

4 Source regions

In 23 of the 40 simulations we have determined possible source regions that are in agreement with previously published works (Morbidelli & Moons, 1995; Hahn et al., 1991; Galiazzo et al., 2013). The four main regions were the 3:1 and 5:2 mean motion resonance with Jupiter, the ν_6 secular resonance, and the Hungaria family of asteroids.

According to other authors (Granvik & Brown, 2018), most meteorites are delivered to Earth via the 3:1 and

[1] As of October 2022 via https://www.lpi.usra.edu/meteor/.
[2] List of published meteorite orbits https://www.meteoriteorbits.info/.

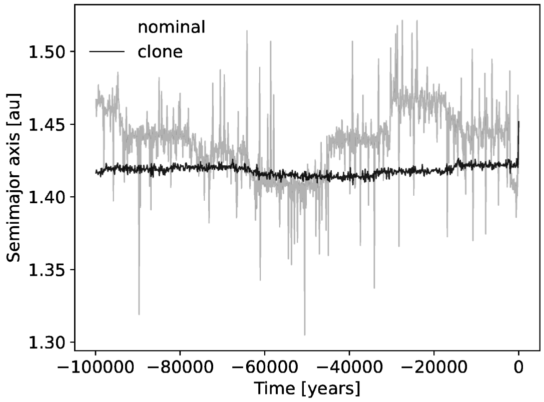

Figure 1 – Time evolution of the semi-major axis of the Novo Mesto meteorite, the nominal particle evolution (black line) and mean evolution of 99 clone particles (grey line).

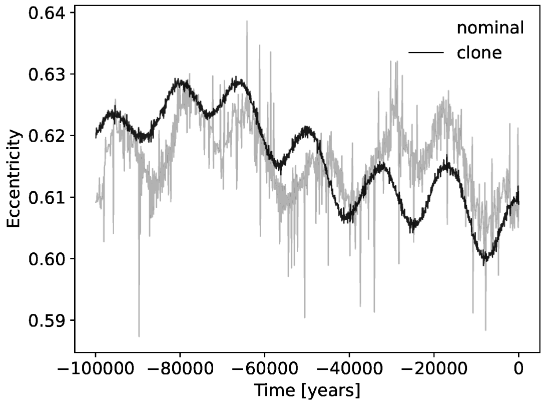

Figure 2 – Time evolution of the eccentricity of the Novo Mesto meteorite, the nominal particle evolution (black line) and mean evolution of 99 clone particles (grey line).

ν_6 resonances. They were also the most common escape routes in our simulations.

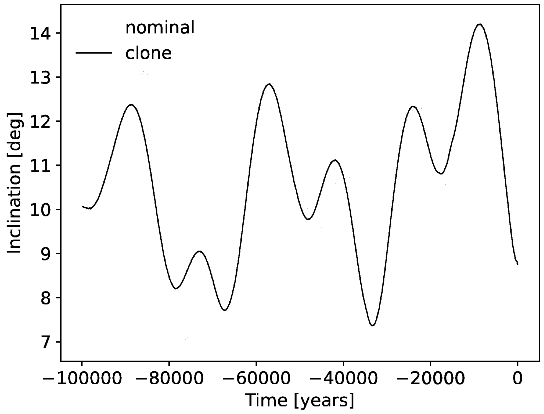

Figure 3 – Time evolution of the inclination of the Novo Mesto meteorite, the nominal particle evolution (black line) and mean evolution of 99 clone particles (grey line).

The remaining 17 simulations displayed only low-integer mean motion resonances with Jupiter (e.g. 7:1, 8:1, 6:1, etc.).

5 Parent bodies

For both the D-criteria used, we set the cut-off value to 0.15. Using the Southworth-Hawkins D-criterion we have found possible near-Earth asteroid[3] connections for all 40 meteorites. Three NEAs showed significantly lower values of the D-criterion of $D_{SH} \leq 0.01$. They were 2021 GG1 with the Križevci meteorite (Borovička et al., 2015), 2019 SP3, and 2021 TX10, both with the Mason Gully meteorite (Spurný et al., 2012).

Applying the Southworth-Hawkins and Rudawska D-criteria on the IAU MDC database of meteor showers, we have found possible associations for 30 meteorites using the former, and 6 meteorites using the latter criterion. One meteor shower, omega Cassiopeiids, showed very low values of both the D_{SH} and the D_X criteria with the Innisfree meteorite (Halliday et al., 1978).

6 Conclusions

We have performed numerical simulations to study the 40 pedigree meteorites known at the time, mainly their possible source regions. Our findings were in agreement with other authors in most cases, showing the 3:1 mean motion resonance and the ν_6 secular resonance as the most common escape routes of these meteorites.

Using the similarity criteria, we have found a number of interesting associations with meteorites Križevci, Mason Gully, and Innisfree. However, the low values of the D-criteria do not guarantee a connection. There are plans to study the candidates in the near future.

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[3]Minor Planet Center NEA database.