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DIMS Experiment for Macroscopic Dark Matter and Interstellar Meteoroid Study

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DIMS is an experiment aiming to search for macroscopic dark matters and interstellar meteoroids. Nuclearites are nuggets of stable strange quark matter, hypothetical super-heavy macroscopic particles (macros), and possible important components of the dark matter in our Universe. The velocity of the nuclearites is expected to be around 220 km/s in our galaxy, whereas the velocities of the interstellar meteoroids may exceed the escape velocity of the solar system by only several km/s. We are studying the possibility to search for such fast-moving particles by using very high-sensitivity CMOS cameras with a wide field of view. We estimate the observable mass ranges and flux limits for the moving nuclearites and the interstellar meteoroids from observed data. At the 1st stage we set up 3 high-sensitivity CMOS camera stations with a separation distance of about 100 km at the central area in Japan, at the 2nd stage 2 stations were added with a separation distance of 17 km at the Telescope Array (TA) cosmic-ray-experiment site in Utah, USA, and at the 3rd stage 2 stations were relocated from Japan to the TA site. We have been remotely operating over one year with such multiple stations. Details of the project science, present status and some results are reported in this paper.

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1. Introduction

1.1 Macroscopic Dark Matter

As a form of dark matter (DM) highlighted by [1], it is possible for DM to exist as particles with high masses and cross sections but low number density. Such a category of "macroscopic" DM is known as "macro" (e.g. [2]). Macros are assumed to interact with ordinary matter only geometrically and lose their kinetic energy. Several macro models are based on the hypothesis of strange quark matter (SQM), which is composed of up, down, and strange quarks. For instance, the high pressures within neutron stars' cores could create favorable conditions for SQM formation. Additionally, if SQM is more stable than ordinary matter, neutron stars could convert most of their baryonic content into strange matter, leaving only a thin outer layer of ordinary nuclei [3].

Astrophysical events such as neutron star collisions or the merging of binary systems of neutron stars could produce fragments of SQM with arbitrary dimensions and velocities known as nuclearites [4]. They could be trapped in the gravitation of our galaxy and typically have a velocity of 250 km/s near the Earth, corresponding to the rotation velocity of our galaxy near the Sun. When passing through the Earth's atmosphere, they would deposit part of their energy as luminous radiation, appearing much faster than meteoroids bound to the Sun's gravitation. The heliocentric velocity of the most meteoroids is within ~42 km/s, which is the escape velocity from the solar system at Earth's orbit.

So far, several groups reported upper limits on their fluxes in different mass ranges. The DIMS (Dark matter and Interstellar Meteoroid Study) experiment exploits this characteristic to search for meteor-like events associated with the passage of a macro in the atmosphere. The amount of energy released as light depends on the specific model for light emission and the density of these objects [2]. The model of Ref.[4] indicates a constant light emission in the lower atmospheres that appears an apparent magnitude ranging between ~1 and ~6 for a 1-g nuclearite for a distance range of 1–10 km. This model indicates, furthermore, such heavy nuclearites may even penetrate the Earth and be distinguished by detecting upward-moving events.

1.2 Interstellar Meteoroids

As the solar system moves through the Local Interstellar Cloud (LIC) [5], it comes across interstellar dust particles traveling at speeds of approximately 26 km/s, reflecting the Sun's velocity relative to the LIC [6]. During this journey through interstellar space, the solar system may also encounter larger particles — meteoroids, which have been ejected from other planetary systems [7]. The speeds of these interstellar meteoroids at the edge of our system would correspond to the relative velocity of the stars with respect to the Sun and would be influenced by the ejection velocities. When measured by a detector on Earth, the speeds include an additional component resulting from the meteoroids' fall into the Sun's potential [8]. In any case, the heliocentric speeds of interstellar meteoroids exceed the parabolic velocity by several kilometers per second. However, their geocentric velocities can span the entire range of possible collisional velocities between two objects within the solar system, ranging from 12 km/s to 72 km/s, and they may exceed this range. Confirming the interstellar origin of a meteoroid observed as a meteor in Earth's atmosphere is exceedingly challenging [9]. This difficulty arises from the fact that the hyperbolic excess in the heliocentric velocity, which serves as an indicator of interstellar origin, is a small quantity that currently remains within a similar magnitude as typical measurement errors [10].

The influence of errors on the resulting orbits of meteoroids can lead to the emergence of a spurious population of non-real hyperbolic meteors [10]. Currently, only a limited number of meteor networks, like the European Fireball Network [11], Canadian Automated Meteor Observatory [12], the Global Meteor Network [13], and the Czech Catalog of Video Meteor Orbits [14], are capable of providing velocity measurements with an accuracy of 100 m/s or better. With such precise data, after excluding hyperbolic meteors resulting from processes within the solar system [15], it may be possible to identify a sample or individual cases of interstellar particles. For this reason, it is crucial to enhance techniques and establish new networks that can attain the desired level of accuracy.

2. DIMS Experiment

2.1 Observation concept

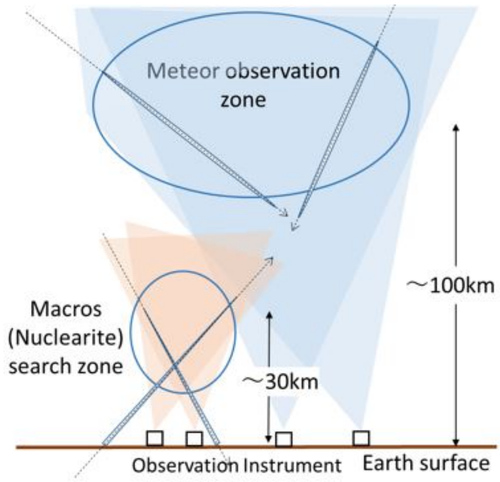

Figure 1: Observation concept of the DIMS experiment.

We have initiated the DIMS experiment to observe light emitted from meteoroids and nuclearites as they pass through the atmosphere [16]. Observation concept of the experiment is shown in Fig.1. There are significant differences in their emission mechanisms and velocities between them, which makes them easily distinguishable. The meteoroids evaporate when they enter the atmosphere and emit light due to the ionized gas. On the other hand, the nuclearites are expected to collide quasi-elastically with ambient atoms, causing black-body radiation from an expanding cylindrical thermal shock [4]. Since the ordinary meteoroids are bound within the solar system, their heliocentric velocity is less than 42 km/s. In case of interstellar meteoroids their heliocentric velocities are larger than 42 km/s. In addition, since the orbital velocity of the earth is 30 km/s, the geocentric velocity of ordinary meteoroids range from 12 to 72 km/s. In contrast to these cases, the macros such as the nuclearites are bound in our galaxy, and their typical velocity is about 250 km/s in the galactic frame, which is much faster than any meteoroids. Also, meteoroids have an emission altitude of about 100 km, whereas the nuclearites have an emission altitude of about 30 km or less for the masses we are interested in. Finally, the most significant difference between the two is that the meteoroids do not penetrate the Earth, while nuclearites with masses greater than 0.1 g have the potential to penetrate the Earth. As a result, the nuclearites may make upward trajectories from the Earth's surface to the sky.

2.2 Experiment apparatus

To observe these fast-moving, faintly luminous objects, we use 3 types of high-sensitivity camera modules. Figure 2 shows pictures of the camera modules. Each module of type (a) or type (b) in the figure consists of a Canon ME20F-SH monochrome camera or ME20F-SHN color camera with a 35mm f/1.4 wide field lens, a PC and many other parts. These parts are installed in a thermally insulated stainless steel box with a glass window. The type (c) module mainly consists of the high sensitivity camera and the PC and HDD's are installed in a separate outer box to avoid the thermal and light influences of the sun.

Though the maximum ISO sensitivity of the camera is 4 million equivalent, we set the ISO sensitivity at around 204,000 for the actual observation because the noise level increases more as the sensitivity increases. We operate the cameras with video mode at a frame rate of 30/s in order to obtain the velocities of the observation objects. Accurate velocity and trajectory of each event can be obtained by stereo observation using multiple camera modules. Each camera module has a wild field of view (FOV) of 56.2°×33.4°. Details of the camera system, the environmental monitor and the control system are described elsewhere [17, 18].

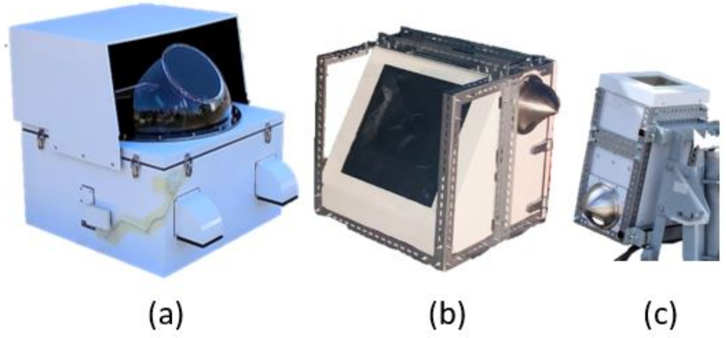

Figure 2: Three types of DIMS camera modules.

2.3 Observation site

The observation systems of the DIMS experiment have been deployed at the central area in Japan and the Telescope Array (TA) high-energy cosmic-ray experiment site [19] in Utah, USA (Fig. 3). Due to the influences of COVID-19 three camera systems were installed at Kiso Observatory, Akeno Observatory, and Shinshu University in Japan at the beginning stage of the experiment. Then, two camera systems each were installed at Black Rock Mesa (BRM) and TARA of the TA site in Utah. Base line distances between them are from 16.7 km to 108 km. Since there is no

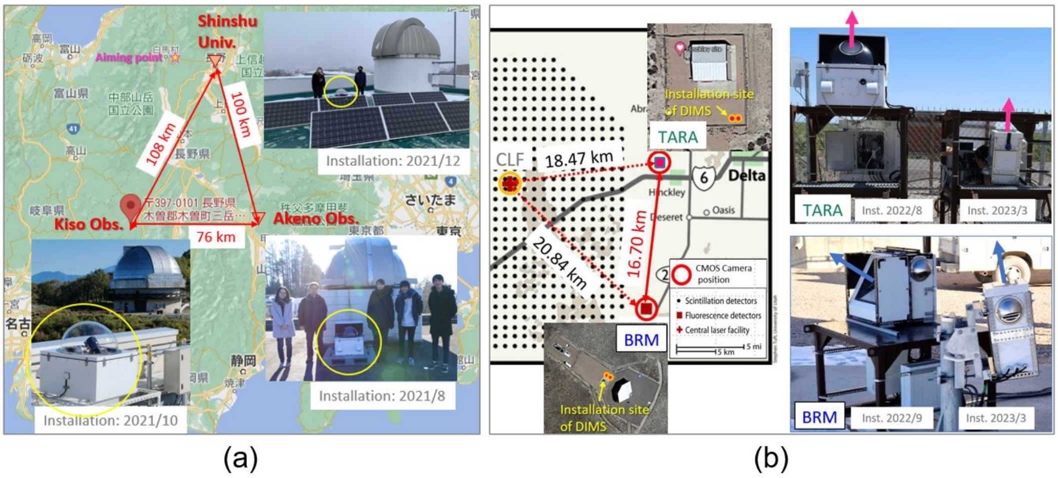

Figure 3: Observation site in Japan (a) and at the TA site in Utah (b).

power lines from the electric power company at the CLF site, we developed an electric power self-sufficiency system using solar power generation [20, 21].

2.4 Observation

Observations at Akeno and Kiso Observatories began from August 2021 and at Shinshu Univeristy from December 2021. The observations at Akeno and Kiso were terminated to relocate their cameras to Utah in January 2023. The observations at TARA and BRM began from September 2022 and at TARA with the 2nd camera and BRM with 2nd camera began from Feburuary 2023.

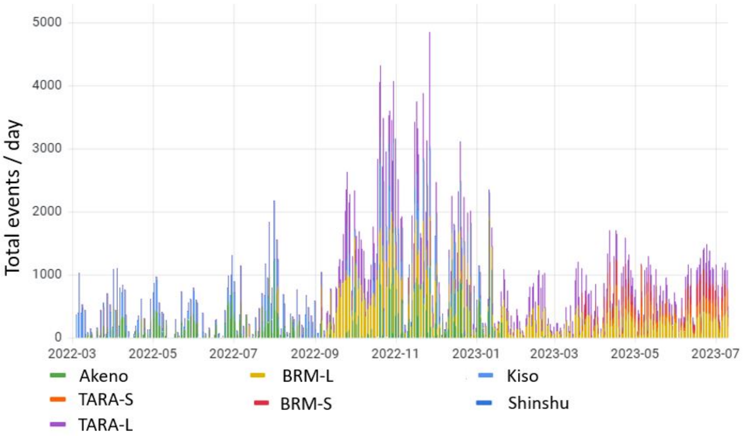

Figure 4: Total events per day vs. date for 16 months.

Figure 4 shows total triggered events per day taken by the DIMS cameras as a function of date from the beginning of March 2022 when the online data acquisition (DAQ) monitoring system has been installed. On a dark, cloudless night during the new moon, we were able to observe about 1,000 meteor events per camera per night.

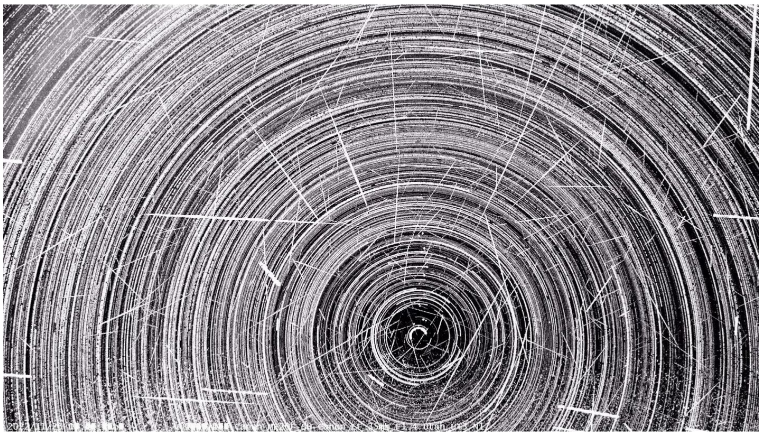

Figure 5: Composite picture of triggered events taken at the TARA site in one night.

Figure 5 shows an example of a composite picture of triggered events take at the TARA site in Utah on the night of November 26th 2022. This picture contains a total of 1,751 trigger events, and there are nearly as many meteor events here.

3. Data Analysis

Analysis of DIMS data has been carried out mainly by 3 methods. The first one has been performed by developing a program using astrometric and photometric calibrations similar to the one for the all-sky cameras of the PRISMA fireball network [22]. The second one has been performed by the program originally developed by our group [18]. The third one has been performed using UFOAnalyzer to obtain parameters such as magnitudes and angular velocities of meteors, and UFOOrbit to obtain parameters such as velocities and orbits in the solar system. [25]

4. Preliminary Results and Discussion

Some preliminary results, including meteor height, velocity, magnitude distribution, cross section of nuclearite mass, and the interstellar meteoroid have been published elsewhere by analyzing data taken for one night at the TA site in Utah using the first analysis method described above [22–24].

As an example, magnitude of meteors as a function of angular velocity analyzed using UFOAnalyzer is shown in Fig. 6 for the data observed at Akeno Observatory in the period from November 1st 2021 to January 2nd 2023 for 155 days. There are 23,095 data points in this figure. We are able to observe meteors efficiently in the upper region of the red line. If there are candidates of macros they will be shown in the upper right region of this figure. We are now carefully investigating if such candidates exist in this area.

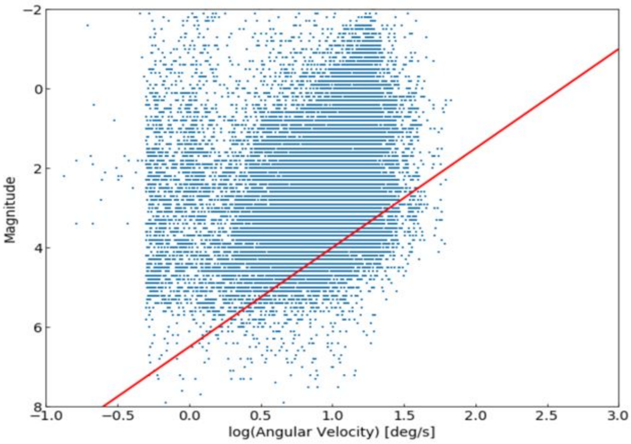

Figure 6: Meteor magnitude vs. angular velocity of meteors.

Heliocentric velocities of meteoroids were obtained by using both of the data observed at Akeno and Kiso Observatories in the period from May 27th 2021 to October 3rd 2022. There were 19,453 meteor events in the Akeno data set and 30,352 in Kiso. After very stringent conditions applied to these data sets we obtained 793 coincident events using UFOOrbit. A very preliminary result from a distribution of the heliocentric velocity of meteoroids are shown in Fig. 7. Though there are some events with high heliocentric velocity in a region of the interstellar meteoroid candidate, we are carefully examining each candidate at present.

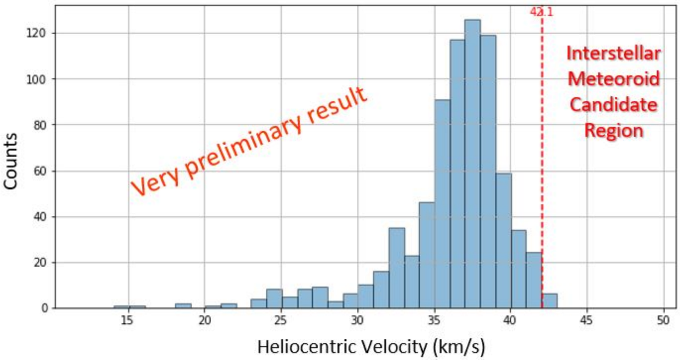

Figure 7: Distribution of heliocentric velocity of meteors.

5. Conclusion

We are carrying out the DIMS experiment to search for the macroscopic dark matter such as the nuclearite and the strange quark matter, and also to search for the interstellar meteoroids by setting arrays of very high sensitivity CMOS camera systems at the central area in Japan at the first stage, then in the TA site in Utah at the second stage. The observation started at Akeno and Kiso Observatories in Japan from August 2021, and at the TA site in Utah from September 2022. The observation is continuing at the TA site using 4 camera systems by a remote control and taking lots of data automatically at present.

Data analysis is underway by mainly 3 methods. Some preliminary results obtained from the data taken in Japan is shown in this paper and those obtained in Utah elsewhere [18].

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