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Study of Fast Moving Nuclearites and Meteoroids using High Sensitivity CMOS Camera with EUSO-TA

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Nuclearites are hypothetical super-heavy exotic particles and may be important components of the dark matter in our Universe. They are expected to have typical geocentric velocities of ~220 km/s, if they exist. Interstellar meteoroids are other interesting bodies, which can be distinguished from solar system meteoroids based on geocentric velocities larger than the limit of 72 km/s, corresponding to the sum of escape velocity from the solar system and the velocity of the Earth around the Sun. We have been studying the feasibility to search for such fast moving particles by using very high sensitivity CMOS cameras. We also propose co-observations with EUSO-TA to check the slow trigger application and to help the analysis of the observational data of EUSO-TA.

We observed many meteor events by a single and a stereo camera system. We can estimate the observable mass range of the nuclearites and the interstellar meteoroids from the sensitivity of the camera system for these fast moving events using the observed meteor events. Observable flux limits are estimated for these mass ranges.

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1. Introduction

1.1 Meteoroid

Meteoroids which arrive from outside our solar system, namely from interstellar space, to the Earth would give us an invaluable scientific information. They are small solid particles in outer space and range in mass roughly from 10^{-19} kg to 10^{-3} kg. They have been detected by space based dust detectors, meteor radars, image intensified video equipment and possibly photographic techniques. Determination of the size distribution, influx rate, dominant directions of arrival and physical and chemical makeup of these meteoroids from interstellar space could significantly constrain models of planetary system formation [1].

At the Earth's orbit, the parabolic or escape velocity with respect to the Sun is about 42 km/s and the Earth's orbital speed is about 30 km/s. Therefore, the geocentric encounter speed of the meteoroids with the parabolic orbits could range from about 72 km/s to 12 km/s. It would be expected a heliocentric velocity for a typical interstellar origin meteoroid to be of the order of 47 km/s by taking various factors into account [1].

It has been recently suggested that gravitational scattering of interplanetary meteoroids by the planets can produce them with speeds comparable to interstellar meteors and at fluxes near current upper limits for such events. However, the majority of this locally-generated component of hyperbolic meteoroids is just above the heliocentric escape velocity and should be easily distinguishable from true interstellar meteoroids [2].

1.2 Strange Quark Matter and Nuclearite

Witten pointed out that strange quark matter consisting of aggregates of up, down and strange quarks in roughly equal proportions is more likely to be stable than non-strange quark matter [3]. These nuggets of strange quark matter may be stable for almost any baryon number (A), including values intermediate between those of ordinary nuclei ($A < 263$) and neutron stars ($A \sim 10^{57}$). He suggested that nuggets of the quark matter could be produced in the first-order cosmological quark-hadron phase transitions in the early Universe (unlikely) or in processes related to compact stars such as neutron stars or quark stars (more likely). He also suggested the possibility that such nuggets could solve the cosmological dark matter problem.

De Rújula and Glashow used the term 'nuclearite' which is considered to be large neutral strange quark nugget covered by an electron cloud. Quark nuggets, nuclearites and strangelets are different names for lumps of a hypothetical phase of absolutely stable quark matter, so-called strange quark matter. They suggested some experiments to detect them which would show up as unusual meteor like events, earth-quakes, and etched tracks in old mica, in meteorites and in cosmic-ray detectors [4].

Several experiments have attempted to search for strangelets in cosmic rays. While some interesting events have been found that are consistent with the predictions for strangelets, none of these have been claimed as real discoveries [5]. Massive nuclearites may pass through the Earth and they may be detectable by seismic signals they generate [4]. Anderson et al. reported an event that has the properties predicted for the passage of a nugget of strange quark matter through the Earth, although there is no direct confirmation from other phenomenologies [6].

De Rújula et al. calculated the luminosity of the nuclearites when they pass through the atmosphere. The amount of light along the track is also quite different between the nuclearites and meteors. The nuclearites may have a typical velocity of ~220 km/s near the Earth, whereas the geocentric velocity of the meteoroids bound in the solar system is at most about 72 km/s. Therefore, they will be able to be distinguished well from the observed data.

In this paper, we tried to investigate the possibility of studying the interstellar meteoroids and strange quark matters or nuclearites using state-of-the-art high sensitivity CMOS camera. Co-observation with EUSO-TA [7] is also an interesting study to check the experimental instrument and analysis methods by the observation of meteor events.

2. Experimental Apparatus

Recent technical development of the CMOS camera is very rapid. We used one of the most sensitive CMOS camera, Nikon D5, in this experiment. Main specifications of the camera system we used are listed in Table 1. ISO sensitivity of the camera can be set up to 102,400 and it can be additionally set up to ISO 3,280,000 equivalent with lower image quality. The image sensor size is 35.9 x 23.9 mm full-frame. Maximum lens aperture is f/1.4.

Camera images are sent to a video capture module through HDMI cable at a rate of 60 fps with a frame size of 1920×1080 and then to a PC through a USB cable (Fig. 1). HDMI (High-Definition Multimedia Interface) is an audio/video interface for transmitting uncompressed video data, and compressed or uncompressed digital audio data from a HDMI-compliant source device. We used AVerMedia HDMI video capture module, CV710, which is compatible with USB 3.0 with a maximum image resolution of 1920×1080 at a transfer rate of 60 fps, and which supports a recording format of uncompressed AVI. The PC has specifications of 3.4-3.6GHz 4 core CPU, 16GB memory and 500GB SSD.

Though cooled CCD image sensors and raw image format are often used for astronomical observations, we selected to use a camera with a CMOS image sensor and a HDMI interface for image transfer, because we took the priority on high frame rate, high data transfer rate and large sensor size to collect more photons for the present experiment.

As it is important to determine the velocity of the luminous object for the observation of interstellar meteors and for the search for nuclearites, we used two sets of similar observation systems at two observation locations.

We have chosen to use a time shifted motion capture software UFOCaptureHD2 [8] among several candidate video softwares [9] to detect and record the meteor events on the PC. Number of head frame before the event trigger start was set to be 30, and that of tail frame after the event

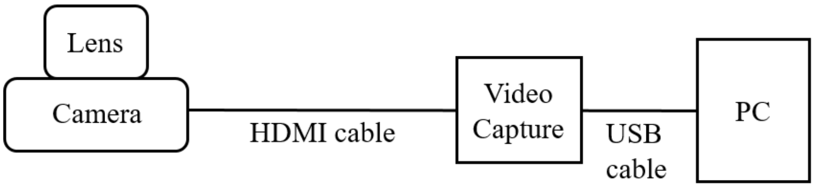

Fig. 1 Schematic view of the observation system. Two systems were employed for the present observation.

Table 1 Main specification of the camera system

Part	Item	Specification
Camera : Nikon D5	Image sensor	35.9 x 23.9 mm CMOS sensor
	Effective pixels	20.8 million
	ISO sensitivity	ISO 100 to 102,400 Settable to ISO 3,280,000
	Movie frame size (pixels) and frame rate	3840 x 2160 (4K UHD); 30p (progressive) (max.) 1920 x 1080; 60p (max.) etc.
Lens : AF-S NIKKOR 35mm f/1.4G	Maximum Aperture	f/ 1.4
Camera System	Field of View (FOV)	52.4° ×29.4° for HDMI output

trigger end was set to be 30. Number of the frame interval to compare two video images to detect the motion was set to be 1. Scintillation mask option was used to reduce the effect of blinking stars automatically in night sky. This real time function determines the position of long term bright object such as fixed starts in FOV, and mask it with a few pixel around it to avoid a influence of the scintillation caused by atmosphere. It improves the motion detection sensitivity dramatically. There are 3 threshold levels concerning the video image trigger, detection level, detection size and duration of change. The detection level is the brightness difference value between two frames of the same pixel, which is automatically controlled by a detection level noise tracking function. The detection size is the number of pixels that have changed more than the detection level, which was set to be 3. Minimum number of continuously changed frames by which video trigger should be asserted, was set to be 2. Triggered events are recorded with uncompressed AVI format in SSD.

3. Observation method

We have observed Quadrantids (QUA) meteor shower from 1st to 4th, Jan., 2017 to examine the performance of the observation system simultaneously at two locations, A and B, 20.33 km away, in Hyogo, Japan, which is shown in Fig. 2. Main information of Quadrantids in 2017 is listed in Table 2 [10], where r is the population index, an estimate of the ratio of the number of meteors in subsequent magnitude classes, and ZHR is Zenith Hourly Rate.

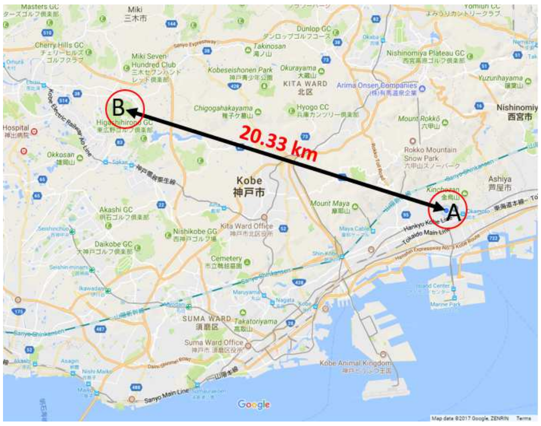

Fig. 2 Observation locations (Map data ©2017 Google, ZENRIN)

A typical example of the coincident meteor event is shown in Fig. 3. This event was taken at the location A and B at 2:02:49, 4th Jan. 2017 (JST). Polaris (mag 2.0), Mizar (mag 2.2) and the apparent radiant position of Quadrantids (star mark) are also shown in the same figure. This meteor event is seen to be originated from the radiant position, as the shower meteors are usually expected.

Table 2 Main information of Quadrantids (QUA) in 2017.

Activity Period	Maximum		Radiant		Velocity	r	Max.	Time	Moon
	Date	S. L.	R.A.	Dec.	km/s		ZHR		Date
Dec 28 - Jan 12	Jan 03	283.16°	15:24	+48.7°	40.9	2.1	120	0500	05

Fig. 3 An example of the coincident meteor event.
Left: observation data taken at location A, Right: observation data at location B

4. Results and Discussion

We observed about 80 meteors by summing the events at locations A and B in total in this period. Classification of these observed meteor events are listed in Table 3, where the shower events are seen to be originated from the radiant whereas the sporadic events are seen to be coming from random direction. Main reason that the number of coincident meteor events are much smaller than total number of meteor events is that effective time to observe the same direction by two systems simultaneously was much shorter than total observation time.

Table 3 Classification of the observed number of meteor events

	Number
Total number of meteors	~80
Shower meteors	~34
Sporadic meteors	~46
Coincident meteors	13

Distributions of apparent magnitude of stars observed at locations A and B in each typical averaged image of 69 images taken with time duration of 1.2 s are shown in Fig. 4. We set the ISO sensitivity of the CMOS camera to be 102,400 for the present observation. Brightness of the night sky at both locations is very much affected by city light of Kobe. If we could observe at a darker location, we could further raise the ISO sensitivity. As the analyzed image is the average of many consecutive images taken with 1/60 s, not the integrated image in time, the apparent magnitude is also limited to be about 6 mag.

To obtain the magnitude from the observed meteor video images at the brightest position along the meteor track, we used a meteor image analysis software UFOAnalyzerV2 [8] which utilizes a star catalog, SKY2000 Master Catalog Version 4 V/109 [11], containing an extensive compilation of information on almost 300,000 stars brighter than 8.0 mag. Distributions of magnitude of meteors observed at locations A and B are also shown in Fig. 4.

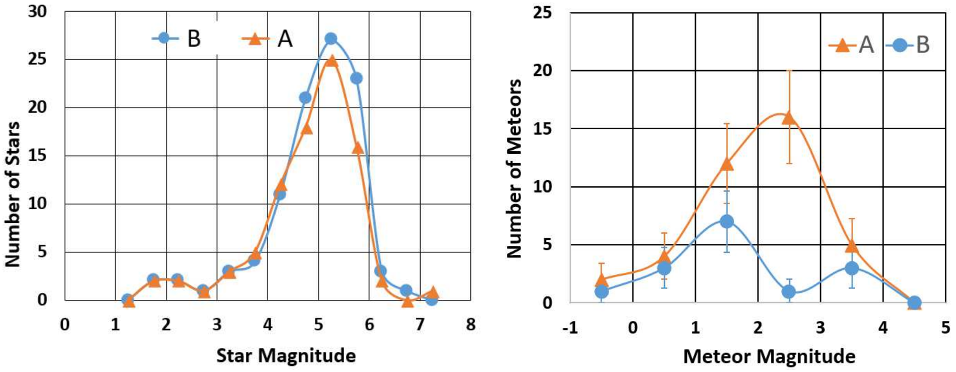

Fig. 4 Distributions of magnitude of observed stars (left) and magnitude of observed meteor events (right).

Difference of number of events in this figure depends mainly on the difference of observation time between A and B. One of the reasons that the observable meteor magnitude is smaller than the observable star magnitude is an effect of triggering meteor events. Limit magnitude for observing meteor events is obtained to be about 3 mag for the present experiment.

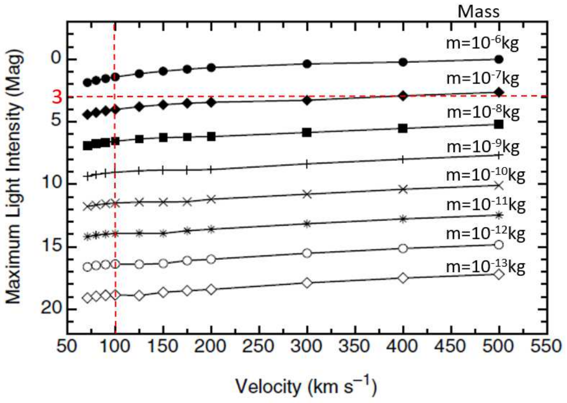

Fig. 5 Maximun light intensity of meteors vs. their velocity for various masses of the meteoriods [12].

Hill et al. suggested that at least high geocentric velocity meteors larger than about 10^{-8} kg should be observable with current meteor electro-optical technology although there may be observational biases against their detection [12]. They showed the maximun light intensity of meteors as a function of their velocity for various masses of the meteoriods (Fig. 5). If the meteor has a velocity sufficiently larger than 72 km/s, it will be originated from outside our solar system.

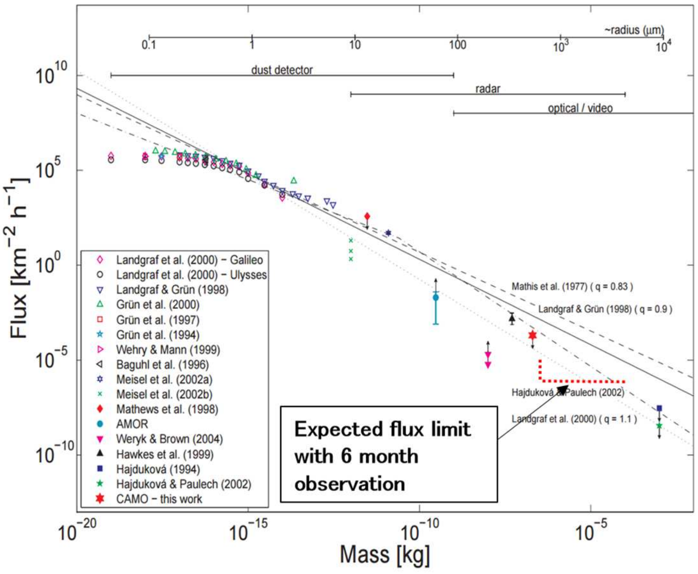

Fig. 6 Expected flux limit for the observation of interstellar meteoroids.

Assuming the observable maximum light intensity to be

3 mag for the meteor velocity of 100 km/s, the observable meteor mass is obtained to be $10^{-6.6}$ kg using Fig. 5.

Observable effective area S_{eff} of the system at 100 km away vertically upward is obtained to be roughly 2.6×10^3 km^2 taking into account the following factors. (1) Typical luminous height of the meteors is roughly 100 km. (2) Present observation system has the FOV of 52.4° ×29.4°. (3) Efficiency to observe the meteors by the system is 0.5.

Expected flux limit for observing interstellar meteors will, therefore, become about 1.0×10^{-6} km^{-2} h^{-1} for the observation period of 6 month at mass region larger than $10^{-6.6}$ kg by assuming that the efficiency of the observation time is 0.09. This limit is drawn in Fig. 6 with many other experiments [13].

Nuclearites, like meteors, produce visible light as they traverse the atmosphere [4]. The apparent magnitude $\mathcal{M}$ of a nuclearite with mass M which traverses with a velocity about 250 km/s at a distance h from an observer is calculated as

$$\mathcal{M} = 10.8 - 1.67 \log_{10}(M / 1\mu\text{g}) + 5 \log_{10}(h / 10\text{ km}). \qquad (1)$$

Nuclearites essentially produce light at much lower altitude than meteors. An upper limit altitude $h_{\max}$ at which nuclearites effectively generate light is calculated as

$$h_{\max} = 2.7\text{ km} \ln(M / 1.2 \times 10^{-5}\text{ g}). \qquad (2)$$

Observable effective area S_{eff} of the system 10 km away vertically upward is obtained to be roughly 26 km^2, taking into account the typical observation height of the nuclearite as 10 km, FOV of the system, and efficiency to observe them by the system as 0.5. Expected flux limit for searching nuclearites will, therefore, become about 4.3×10^{-19} cm^{-2} s^{-1} sr^{-1} for the observation period of 1 year by assuming efficiency of the observation time is 0.09. Mass limit for observing these nuclearites are obtained to be 4.7×10^{-2} g by assuming the observable apparent magnitude is 3 mag using formula (1). Other cases of the observation heights of 1 km and 30 km are calculated similarly. These limits are drawn in Fig. 7 with other experiments [13, 14, 15].

We show 3 types of expected flux limits in the figure because observable height of nuclearites depend on their mass. The upper limit altitudes $h_{\max}$ with the minimun masses of nuclearites $M = 4.8\times10^{-5}$ g for $h = 1$ km, $M = 4.7\times10^{-2}$ g for $h = 10$ km and $M = 1.26$ g for $h = 30$ km, are corresponding to 3.7 km, 22 km and 31 km, respectively. Galactic dark matter flux limit is also shown in the figure. From this figure it is found we are able to search for the nuclearites in the mass range from ~10^{-4} g to ~10^2 g.

We are attempting to obtain velocities and 3 dimensional trajectories

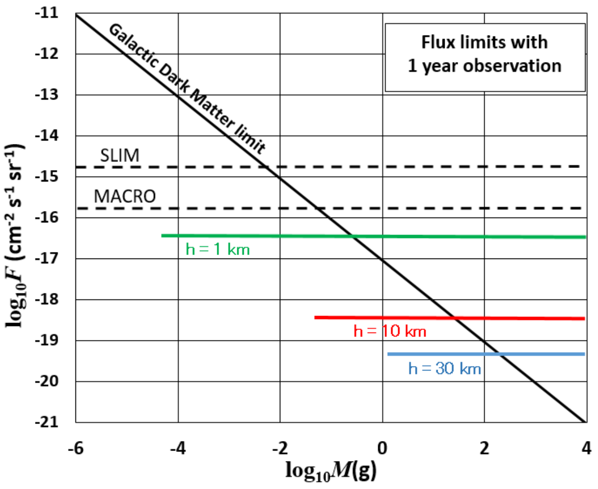

Fig. 7 Expected flux upper limits for nuclearites. A local DM energy density of ρ = 0.3 GeV/cm^3 is assumed for galactic dark matter limit.

of meteor events using multiple observation systems we are currently developing.

The possibility to perform observations of meteors and nuclearites from space has been investigated by the JEM-EUSO Collaboration [16]. Furthermore, we already observed several meteor events by EUSO-TA instrument in ~130 h of observation without dedicated trigger for meteors. The opportunity to operate the present equipment in conjunction with the EUSO-TA instrument is also under study.

5. Conclusion

We have observed meteors in the active period of Quadrantids (QUA) between Jan. 1st and Jan. 4th in 2017 at two locations in Japan using two systems of high sensitivity CMOS cameras. We observed about 80 meteors in total and found their observable apparent magnitude to be about 3 mag. We obtained expected flux as a function of mass for the observation of interstellar meteoroids and search for nuclearites using these results.

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