Nuclearite observations with JEM-EUSO

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Abstract: JEM-EUSO is expected to produce results of utmost importance for a wide and heterogeneous scientific community which includes theoretical and experimental physicists, high-energy astrophysicists, solar system specialists and experts of atmospheric phenomena. The main objective of the mission is to detect extremely high energy cosmic rays, gamma rays, and neutrinos. However, the detector is sensitive also to much-slower-velocity events such as 'nuclearites' or other massive quark-nuggets particles with interaction similar to nuclearites, which consist of neutral matter including a strange quark among its constituents. We focus in this paper on nuclearites because they are an example of particles already studied and searched for by other experiments. In this contribution we show that JEM-EUSO is sensitive to 'nuclearites' with mass $m > 10^{22}$ GeV/c^2 and that a null observation of those class of events in just one full day of data taking will allow to set limits on their flux one order of magnitude more stringent than what has been obtained so far by other experiments. This search can be done at practically no extra cost and is a great example of the multi-disciplinary capabilities of the JEM-EUSO mission.

Keywords: Nuclearites, JEM-EUSO, Space Detectors

1 Introduction

During the last decade a very large experimental and theoretical effort has been devoted to understand the problem of dark matter (DM). Recently, composite objects consisting of light quarks in a color super-conducting phase have been suggested. In addition, super-heavy DM anti-quark nuggets could exist and could perhaps solve the matter-antimatter asymmetry [1]; the detection of such anti-quark nuggets by cosmic ray experiments is discussed in [2]. Recently the possibility to have meteor-like compact ultra-dense quark-nuggets objects dressed by normal matter has been suggested [3]. The energy loss predicted for super-heavy DM particles varies in different models, but it is likely that such particles could be confused with meteors, since the velocity, 270 km s^{-1}, is higher, but of the same order of magnitude of the fastest meteors.

Here, we will focus our attention only on the kind of very massive particle called 'nuclearite'. This consists of neutral matter including a strange quark among its constituents. We make this choice because nuclearites are an example of particles already searched for by other experiments, and for which we can be able to compute some expected performance improvements which should be possible using JEM-EUSO as a possible detector.

Nuggets of Strange Quark Matter (SQM), composed of approximately the same numbers of up, down and strange quarks could be the true ground state of quantum chromodynamics [4, 5].

According to [6] nuclearites are considered to be large strange quark nuggets, with overall neutrality ensured by an electron cloud which surrounds the nuclearite core, forming a sort of atom. Nuclearites with galactic velocities are protected by their surrounding electrons against direct interactions with the atoms they might hit.

As a consequence, the principal energy-loss mechanism for a nuclearite passing through matter is atomic collision. For a massive nuclearite the energy-loss rate is:

$$\frac{dE}{dx} = -A\rho v^2 \tag{1}$$

where ρ is the density of the traversed medium, v the nuclearite velocity and A is its effective cross-sectional area. The effective area can be obtained by the nuclearite density ρ_N. For a small nuclearite of mass less than 1.5 ng, the cross-section area A is controlled by its surrounding cloud of electrons which is never smaller than 10^{-8} cm:

$$A = \begin{cases} \pi \cdot 10^{-16}\,\text{cm}^2 & for\ m < 1.5\ \text{ng} \\ \pi\left(\dfrac{3m}{4\pi\rho_N}\right)^{2/3} & for\ m > 1.5\ \text{ng} \end{cases} \tag{2}$$

where $\rho_N = 3.6 \cdot 10^{14}$ g cm^{-3} is the nuclearite density and m its mass.

According to Eq. 1, nuclearites having galactic velocity and mass heavier than 10^{-14} g penetrate the atmosphere, while those heavier than 0.1 g pass freely though an Earth diameter. Eq. 1 has been used by [6] to compute the amount of visible light emitted in the atmosphere, assuming that the light is emitted as a black-body radiation from an expanding cylindrical thermal shock wave and to compute therefore the apparent magnitude as defined for meteors.

The efficiency of the light emission due to the black body radiation is inversely proportional to the medium density: this cancels the density dependence of the energy-loss

Table 1: Experimental techniques, locations, representative experiments, sensitive area and nuclearite mass thresholds computed for $v = 270$ km s^{-1}.

Technique	location	Experiment	S(m^2)	m$_{th}$ (g)
thermo-acoustic	sea level	[8]	~ 1	10^{-13}
damage	mountain 5230 m a.s.l.	[9]	427	$5 \cdot 10^{-14}$
light in oil	underground 3700 hg cm^{-2}	[10]	$\sim$700	$2 \cdot 10^{-10}$
light in water	underwater 2500 hg cm^{-2}	[11]	$\sim 10^5$	$2 \cdot 10^{-10}$
earth or moon-quakes	earth/moon inner	[12]	$\sim 10^{11}$	$\sim 10^4$

and therefore in most of the nuclearite path in the atmosphere the light emission is constant with height. According to [6] the upper limit to the altitude (h_{max}) at which nuclearites effectively generate light is described by the following relation:

$$h_{max} = 2.7 \ln(m/1.2 \times 10^{-5}\ g)\ \text{km} \quad (3)$$

and for altitudes less then h_{max} the light emitted is constant. For the range of masses 0.1-100 g, h_{max} is expected to be located between 24 km and 60 km.

It turns out therefore that there are three important differences that can help to discriminate between nuclearites and meteors. The first one is that the amount of light emitted by nuclearites is constant at $h \leq h_{max}$, the second difference is that a nuclearite of mass bigger than 0.1 g can move upward and this is extremely unlikely for a meteor; the third difference is that the absolute value of the velocity is higher, with a maximum value of ~ 570 km s^{-1}, while meteors are limited to ~ 72 km s^{-1}.

Nuclearites and similar particles, as for example neutral Q-ball[7], have been searched for using different approaches. The experiments can be characterized by the detection area (S) and by the minimum nuclearite mass that can be detected (m$_{th}$), usually computed for a speed of 270 km s^{-1}. Many techniques, summarized in Table 1 have been used to detect nuclearites: acoustic emission due to the thermal shock in aluminum gravitational wave cylindrical detectors, damages in plastic materials like CR39, Makrofol or Lexan, light emission in oil or sea water, seismic waves induced by big nuclearites. Due to the uncertainties in the energy losses it is important to have different techniques to detect such exotic particles. Table 1 lists the different techniques and a representative experiment of each technique. It is not aimed at being a full list of the experiments done so far to search nuclearites, but it is a reasonable summary of the state of the art in this field.

2 General description of JEM-EUSO payload and focal plane assembly

A general description of the JEM-EUSO telescope [13] has already been given elsewhere in this volume. We recall here only the essential points related to the meteor and nuclearite detection. The role of the JEM-EUSO telescope [14] is to act as an extremely-fast ($\sim \mu$s) and highly-pixelized ($\sim 3 \times 10^5$ pixels) digital camera with a large aperture (a diameter of about 2.5m) and a wide field of view (FoV) of 60°. It works in near-UV wavelengths (290–430 nm).

The optics focuses the incident UV photons onto the focal surface. The focal surface detector converts incident photons into electric pulses. The electronics counts the number of pulses in time intervals of 2.5 μs (Gate Time Unit - GTU) and records it. When a signal pattern is found, a trigger is issued. This starts a sequence which eventually transmits to the ground operation center the signal data recorded within (and surrounding) a selected pixel region.

The combination of 3 Fresnel lenses has an angular resolution of 0.07°. This resolution corresponds approximately to a linear size of 550 m on the ground beneath the ISS located at an altitude above ground of about 400 km.

The Focal Surface (FS) of JEM-EUSO has a spherical shape of about 2.3 m in diameter with about 2.5 m curvature radius, and it is covered by $\sim 5{,}000$ multi-anode photomultiplier tubes (MAPMTs). The FS detector consists of Photo-Detector Modules (PDMs), each of which consists of 9 Elementary Cells (ECs). Each EC contains 4 units of MAPMT (Hamamatsu R11265-03-M64, 2 inches in size, with 8×8 pixels). A total of 137 PDMs are arranged on the FS. A Cockcroft-Walton-type high-voltage supply is used to suppress power consumption, including a circuit to protect the photomultipliers from instantaneous bursts of light, like in the case of lightning or bright fireball phenomena.

The FS electronics system records the signals of UV photons generated by cosmic rays successively in time. A new type of front-end ASIC has been developed for this mission, which has both functions of single photon counting and charge integration in a chip with 64 channels. The FS electronics is configured in three levels corresponding to the hierarchy of the FS detector system: front-end electronics at EC level, PDM electronics common to 9 EC units, and FS electronics to control 137 units of PDM electronics. Anode signals of the MAPMT are digitized and recorded in ring memories for each GTU to wait for a trigger assertion, then, the data are read and sent to control boards. JEM-EUSO uses a hierarchical trigger method to reduce the huge original data rate of $\sim$10 GB/s down to 297 kbps, needed to transmit data from the ISS to the ground operation center.

3 Simulations

One of the exploratory objectives of the JEM-EUSO mission is the observation of atmospheric phenomena such as meteors. For this reason a very simple model of meteor phenomena has been preliminarily developed in order to make it possible to carry out a campaign of numerical simulations aimed at analyzing the kind of signals which may be produced on the JEM-EUSO focal plane in a variety of possible observing scenarios. This simulator is quite useful to estimate the sensitivity of JEM-EUSO in observing nuclearites. The results presented in the following are in fact rescaled from the simulations conducted for meteors [15].

Currently, the response of the detector, including optics and focusing, and the response of the photomultipliers in

Table 2: For different absolute magnitudes (M) of meteors in visible light, the corresponding flux in the U-band are shown (according to the Flux Density Converter of the Spitzer Science Center; details can be found at the web site http://ssc.spitzer.caltech.edu/warmmission/propkit/pet/magtojy/index.html). The corresponding number of photons per second, the number of photo-electrons per GTU, the typical mass of the meteor, and the number of events expected to be observed by JEM-EUSO (the latter is computed assuming a duty cycle of 0.2) are also shown.

magnitude (M)	U-band flux (erg/s/cm^2/A)	photons (s^{-1})	photo-electrons (GTU=2.5μs)$^{-1}$	mass (g)	collisions in JEM-EUSO FoV
7	$6.7 \cdot 10^{-12}$	$4.3 \cdot 10^7$	4	$2 \cdot 10^{-3}$	1/s
5	$4.2 \cdot 10^{-11}$	$2.7 \cdot 10^8$	23	10^{-2}	6/min
0	$4.2 \cdot 10^{-9}$	$2.7 \cdot 10^{10}$	2300	1	0.27/orbit
-5	$4.2 \cdot 10^{-7}$	$2.7 \cdot 10^{12}$	$2.3 \cdot 10^5$	100	6.3/year

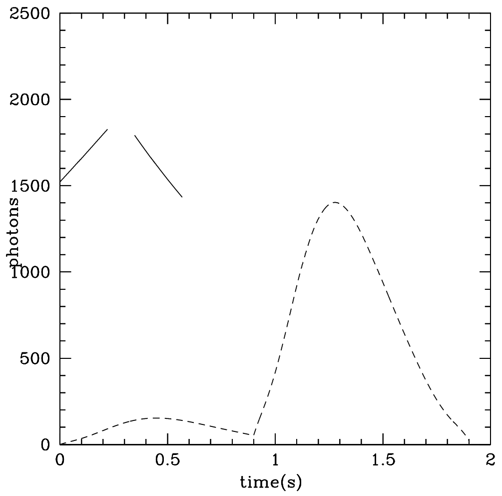

Figure 1: Comparison between the light profile of two nuclearites (thick lines) and that of a meteor (dashed line). The nuclearite has a mass of m = 20 g and velocity of 250 km s^{-1} and it is simulated up-ward going (left curve) and down-ward going (right curve) with θ = 45° inclination from the vertical. The magnitude of the meteor is M = -1, velocity 70 km s^{-1}, and θ = 45° inclination as well.

the focal surface, is parameterized. An overall throughput efficiency of 10% is assumed. An optical point spread function (PSF) of $\sim$2.5 mm is assumed. Cross-talk, pixel-to-pixel non-uniformity response in gain of the order of 10%, as well as poissonian fluctuations of the night glow background are introduced in the simulations. The FS is considered to be a uniform layer of MAPMTs.

Table 2 summarizes the relation between meteor absolute magnitude, photon flux, number of photo-electrons at the maximum of the development, mass and expected number of events in the FoV of JEM-EUSO in the nadir mode.

The simulation work carried out so far suggests that JEM-EUSO could be able to detect meteors down to absolute visual magnitudes of the order of $6-7$, a limit which in absolute terms is not better than the performances of the best ground-based facilities, but which becomes very interesting for meteor science by considering the large FoV and high duty cycle of the JEM-EUSO detector.

4 JEM-EUSO sensitivity to nuclearites

A dedicated simulation of the signals produced by nuclearites moving through the atmosphere is currently under way for a detailed assessment of the expected performances of JEM-EUSO in detecting and recording these events. However, the results already obtained for meteors can be used to draw some general and preliminary conclusions.

First of all, the detection sensitivity to nuclearites can be extrapolated from previous results obtained for the meteors. In particular, the absolute visual magnitude (M) of an atmospheric nuclearite can be computed according to [6] as:

$$M = 15.8 - 1.67 \cdot log_{10}(m/1\mu g). \quad (4)$$

We recall that the absolute magnitude of a meteor corresponds to the apparent magnitude measured on the ground if the meteor is seen at the zenith and at an height of 100 km. By inverting equation 4 it is possible to estimate the minimum mass of the nuclearite detectable by JEM-EUSO in terms of absolute magnitude, which is independent of the distance h. This is reasonable at a first level of approximation, because the maximum difference of apparent magnitudes of the same event in different locations of the field of view is $\Delta M_{app} < 1$. Results indicate that JEM-EUSO is sensitive to objects having mass $m > 0.1$ g when working in single photon-counting mode, and to $m > 3-30$ g when working in charge integration mode. There is of course a dependence upon the sky background luminosity (mainly due to Moon phase).

For what concerns the triggering strategy to be adopted for these events, the same algorithms already developed for meteors can be used, simply varying the total sampling time in order to take into account the shorter duration of the phenomenon (and correspondingly shorter track length). Assuming to be in most unfavorable conditions, namely a nuclearite starting to emit at an height of 60 km, and moving along a trajectory having a zenith angle such that the track crosses the entire PDM along its diagonal ($\sim$42 km) before landing at ground, and taking into account a velocity of 250 km s^{-1}, it follows that the total duration of the phenomenon is only ~ 0.3 s. Therefore, in charge integration mode (KI mode) the optimized condition would be to record the signal during 1024 GTUs, sampled at a rate of one every 128 GTUs, whereas in single photon counting mode, one should record 128 GTU, with a sampling rate of one every 1024 GTUs. In both cases the total integrated time is ~ 0.33 s (one GTU being equal to 2.5 μs). This is a very conservative estimation. In fact, by integrating the signal accumulated in 128 GTU, instead of samping it, a

Table 3: Impact on the relative acceptance (R_{acc}) (see text) as a function of different possible choices of v_{proj}^{min}., assuming a nuclearite velocity $v = 250$ km s^{-1}.

v_{proj}^{min} (km s^{-1})	θ_{min} (deg.)	R_{acc} (%)
100	23.6	84
130	31.3	73
160	39.8	59
190	49.5	42
220	61.6	23

much better performance of the instrument would be obtained.

The most important criterion to distinguish nuclearites from meteors is based on their velocity. Meteors have much slower speeds (in general below 72 km s^{-1}). As it is shown in [15], already at trigger level it is possible to estimate the projected velocity of the signal on the FS with reasonable uncertainty. A subsequent data analysis of the recorded signals will certainly provide much more accurate results. Although it is not possible to derive directly from the data the 3D velocity vector of the source, a limit can be set to the recorded projected velocity (v_{proj}). By requiring that $v_{proj} > v_{proj}^{min}$ and assuming that the velocity of the nuclearite is $v = 250$ km s^{-1}, choosing a value for v_{proj}^{min} automatically sets a limit on the zenith angle of the track $\theta_{min} = arcsin(v_{proj}^{min}/v)$ and relative acceptance $R_{acc} = (1 + \cos(2 \cdot \theta_{min}))/2$. Table 3 shows the relative acceptance as a function of different possible choices of v_{proj}^{min}. It turns out that even a very tight cut on $v_{proj}^{min} > 160$ km s^{-1} makes the acceptance to decrease only by about a factor of 2.

Another important fact to be taken into account is that nuclearites tend to develop at lower heights in the atmosphere compared to meteors. Moreover, any possible evidence of tracks moving upwards would be a clear sign of a nuclearite. The light profile looks also quite different (see Figure 1).

We can expect therefore that JEM-EUSO will be able to set very stringent limits on the flux of nuclearites, even after short acquisition times, due to the tremendous instantaneous exposure (A $\sim 5 \times 10^{20}$ cm^2 s sr) of the instrument. Even adopting a very severe rejection criterion, such as $v_{proj}^{min} > 190$ km s^{-1}, from Table 3 we can infer that for a 24 h accumulation time, a null detection would set a limit in flux at the 90% confidence level of the order of 10^{-20} cm^{-2} s^{-1} sr^{-1} (see Figure 2).

5 Conclusions

Our preliminary analysis concerning the possible detection of nuclearites indicate that JEM-EUSO will be sensitive to nuclearites with mass higher than a few 10^{22} GeV/c^2 and will be able, after a run time of only 24 h, to provide limits on nuclearite flux lower by one order of magnitude with respect to the limits of the experiments carried out so far, and lower than the dark matter limit.

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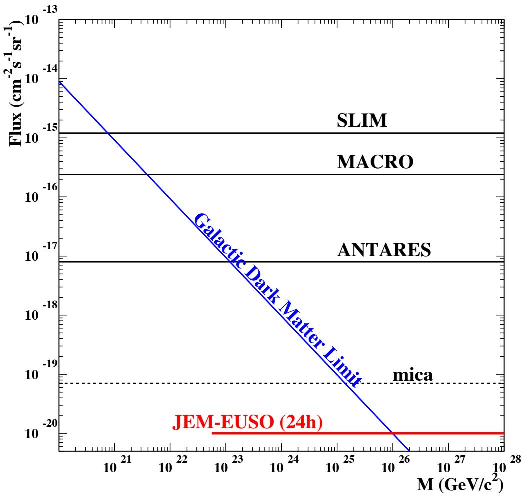

Figure 2: The JEM-EUSO 90% confidence level upper limit on the flux of nuclearites resulting from null detection over 24 hours of JEM-EUSO operations. The limits of other experiments [9], [10], [11], [16] are also shown for a comparison. The old mica limits [16] are dependent from several additional assumptions, respect to the other experiments.

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