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The planned JEM-EUSO mission and applications to meteor observation.

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Abstract. Meteor and fireball observations are important to derive physical information on the population of meteoroids orbiting in the vicinity of the Earth. After decades of ground-based activities, the times seem now mature to plan the development of a new generation of space-based observing facilities for meteor observations. The proposed JEM-EUSO mission has some chances to become the first operational space-based platform having among its objectives the observation of fireball and meteor events. Apart from purely scientific issues, a space-based system capable of fireball surveillance may potentially have also some practical applications for mitigation of the impact hazard in particular circumstances.

Key words. JEM-EUSO – Meteorites, meteors, meteoroids – Space observation – Near UV

1. Introduction

The Earth is subject to a process of continuous bombardment by very small interplanetary bodies generally called meteoroids. Several mechanisms have been discovered and analyzed in recent years to explain a steady influx of bodies from different regions of the Solar System into the zone of the terrestrial planets. In particular, several unstable regions in the space of the orbital elements have been identified in the asteroid main belt. In particular, bodies achieving some critical values (or combinations of values) of their orbital elements, are subject to strong perturbations which force them to chaotically evolve into near-Earth Objects (NEO) (Morbidelli et al. 2002). In this respect, it is interesting to note that geochemical data indicate that the vast majority of meteorites collected on the Earth likely originated from minor bodies having ages comparable with the age of the Solar System (Burbine et al. 2002).

Both collisional mechanisms and dynamical non-gravitational mechanisms, including primarily the so-called Yarkovsky effect, due to the thermal irradiation from the surface (Bottke et al. 2002), can be responsible of a steady injection of main belt asteroids into unstable orbits. It should be noted that the effectiveness of many different supply mechanisms is

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eminently size-dependent. This is trivially true in the case of the Yarkovsky effect, since the acceleration induced by the thermal radiation force becomes progressively less relevant for increasing mass of the object. At the same time, also the average collisional lifetimes of possible meteoroid parent bodies in the asteroid main belt are size-dependent. A better knowledge of the NEO inventory and size distribution down to sizes which are practically not observable by means of remote sensing, therefore, would have important implications for our understanding of the inventory and size distribution of the possible parent populations (main belt asteroids and comets), as well as on the effectiveness of the supply and transport mechanisms in different size ranges.

A major problem, however, is the still scarce knowledge of the size distribution of NEOs at small sizes. The known NEO inventory can be considered as essentially complete above 1 km, but this includes only a minor fraction of the existing objects. Then, it would be very useful to obtain more information on bodies smaller than the current completeness limit. In particular, the size range between 10 and 100 meters corresponds to the least known objects of the Solar System. There is practically little hope to detect objects in this size range but in the case they very closely approach the Earth. Based on current technology, these bodies can be efficiently detected only when they actually collide with the Earth. These events typically occur at a sufficiently high rate to justify a systematic observational effort. The observations of bright meteors and fireballs can thus provide crucial information on the inventory and size distribution of the NEO population in a very important interval of sizes, and can at the same time be used to derive data on the physical properties of these bodies, and on their likely origin.

2. Meteors and fireballs

The vast majority of the bodies hitting the Earth are just dust particles which do not reach the ground, and are mostly visible as meteors in the night sky.

About 75% of the meteor events are sporadic, whereas one fourth of the observed meteors are genetically associated in a number of meteoroid streams producing meteor showers in well defined epochs of the year. This is due to the fact that each meteoroid stream is formed by bodies having very similar orbits, likely produced by low velocity ejection from a common parent body. Many known meteor showers (like the Lyrids and the Perseids to mention only a few of them) are known to be associated with a parent comet. In the case of the Geminids, the parent body is an object previously classified as an asteroid, (3200) Phaeton.

Meteoroids hit the Earth's atmosphere at hypersonic velocities ranging mostly between 11 and 73 km/sec (the escape velocities from the Earth and the Solar System, respectively). Depending on the entry velocity and the mass of the meteoroid, different phenomena are then produced. All of them, in practice, are a consequence of the conversion of the kinetic energy of the impacting body into other forms of energy. As a general rule, there is always a release of ions and free electrons along the meteoroid path through the atmosphere. These are produced by the collisions of the material on the body's surface with atoms and molecules of the atmosphere. In many cases, visible light is produced by de-excitation of these ions. In less frequent cases, corresponding to the most energetic events, additional detection of acoustic and infrasonic blast wave effects is also possible.

The most common outcome of the entry of a meteoroid in the Earth's atmosphere is the meteor phenomenon, which is produced by bodies having sizes which, depending on the entry velocity, are typically larger than some fraction of a mm (Ceplecha et al. 1998). After a preliminary heating at heights between 300 and 100 km (preheating phase), a phase called *ablation* follows, in which the surface material starts to sublimate and a layer of hot vapor is produced around the body, which is heated up to temperatures well above 2000 K. At temperatures around 2500 K evaporation from the melted material starts. Excited states of the ions in this surrounding layer are produced and emit light at characteristic lines while they lose energy and are de-excited. The beginning height of this phenomenon ranges generally between 75 and 120 km. This process continues until the body is completely disintegrated, generally at heights between 30 and 70 km, after traveling a distance which may range from several kilometers up to few tens of kilometers. A typical meteor ends up losing all its mass, though not radically changing its velocity: the latter generally decreases by an amount between several percent up to a few tens of percent. The duration of the phenomenon is generally between 0.5 and 3 seconds. Because ions and free electrons are produced in a ionized column along the path of the body in the atmosphere, it is possible to detect these events also by means of radar techniques.

Whenever the impacting body's size is larger than some limit depending on the entry velocity vector (about 20 cm for a velocity entry of 15 km/sec from the zenith direction), the resulting meteor can be extremely bright. When the apparent brightness of the meteor reaches a magnitude around -8 or brighter at visible wavelengths, it is called *meteoric fireball*. The term *bolide*, or *fireball*, is also generally used to indicate events reaching magnitude -14 or brighter, corresponding to an impactor mass estimated to be between 0.1 and 1000 kilograms. When the magnitude reaches or exceeds -17, corresponding to impacting bodies above $1,000$ kg in mass, the term *super-bolide* is used (Ceplecha et al. 1999).

The amount of energy delivered to the Earth by collision with a meteoroid depends of course on the mass and velocity of the impactor. Assuming an impact velocity of 20 km/s, an object having a mass of $1,000$ kg delivers an energy of about 0.05 kTons, while an object having a mass of 10^6 kg, corresponding to about 10 meters in size, delivers about 50 MTons. According to Ceplecha et al. (1999), over average timescales of the order of 100 years, most of the mass delivered to the Earth by colliding interplanetary bodies comes from super-bolides, having individual masses between 10^3 and 10^7 kg, and typical sizes of the order of 10 meters. Bodies in this size range are the least known population of minor bodies in our Solar system. The number of events involving bodies in this size range is thought to be larger than 50 events per year, justifying a systematic observational effort.

Apart from the very rare and hugely destructive impacts producing craters on the Earth's surface and regional or global devastations, bolides and super-bolides represent the most spectacular events of collision with extraterrestrial material. Since several decades a big effort has been made in order to be able to detect and record the maximum possible number of these events, with the general purpose of being able to determine the three-dimensional entry velocity vector of the bodies, in order to derive their pristine heliocentric orbits, to obtain some information about their composition, derivable from spectra, to derive hints on the ablation mechanisms based on the observed meteor lightcurve, and to record the path in the atmosphere in order to compute also the likely regions of fall of possible associated meteorites. The derivation of the inventory and size distribution of the bodies which can intersect the orbit of the Earth with a non-zero probability of collision with our planet, has been since a long time a high priority task of modern Planetary Science. Apart from obvious considerations about mitigation of the impact hazard for the terrestrial biosphere, this is also a challenging theoretical problem, with important implications for our understanding of the orbital and physical evolution of the minor bodies of our Solar System.

3. The use of orbital devices for the observation of meteors and fireballs

Large networks of ground-based observing stations are needed for visible detection of meteors and fireballs. A lot of work has been done since many years by networks established in many countries, mainly in North America, Europe (European Fireball Network), Japan and Australia. These networks include both amateur and professional observers, and use state-of-the-art detectors, and optics allowing to cover the largest possible field of view. Moreover, bolides are also detected by means of infrasonic and acoustic techniques, which are able to detect the blast wave produced by the delivery of a bolide's kinetic energy into the atmosphere. The resulting blast wave, however, is subject to significant refraction effects due to vertical gradient of the atmosphere's temperature, and to the effect of winds. Although the minimum amount of delivered kinetic energy detectable in ideal conditions is fairly low in principle, the major limit of this technique is the limited range of detection distance for ground-based stations, which is of the order of a few hundreds of km, severely limiting the number of detectable events.

In addition to the above techniques, meteors can also be detected at radio wavelengths, as demonstrated as an example by the Bologna-Modra forward-scatter system (Zigo et al. 2009).

Although all the above-mentioned techniques of meteor and bolide detection using a variety of ground-based stations have great merits and have been successfully operational since many years, this does not mean that they are not affected by a number of serious problems. First, the covered sky area is in any case forcedly limited. Even in the best cases, a single ground-based network for meteor observations covers less than 1% of the Earth's surface. Even assuming that a big effort could be done to improve the coverage, the potentially conceivable development of an all-sky system would in any case face the problem that most of the Earth's surface is covered by oceans. Second, optical observations can be made only during the night or around dawn. Third, the efficiency is affected by the varying weather conditions, including primarily the presence of clouds.

Since a long time it has been clear that fireball events should be in principle best detectable from space-based facilities (Ceplecha et al. 1999). This includes both observations of the light spike at visible wavelengths, and the thermal infrared radiation produced by the heating of the meteoroid material all along its path in the atmosphere. Infrared observations are possible also from the ground, but it is known that space-based detectors work better and more efficiently in the infrared. This is trivially true when sources above the atmosphere are concerned, but also in cases of meteor phenomena, in which the phenomena occur in the high layers of the atmosphere, space-based detectors suffer in any case from much reduced atmospheric extinction at all wavelengths with respect to ground-based facilities.

Of course, space-based sensors have a number of other obvious advantages with respect to ground-based observing stations. They can cover wide areas of sky, and, being located above the atmosphere, a satellite is not limited by weather conditions, and can operate in principle also in day time, at least for the detection of bright events. Given the very big number of satellites currently in orbit, it can seem strange that fireball detections have not been routinely reported so far. The reason is that existing satellites are dedicated to other purposes, and it is not usual that meteor events are detected and recorded. Most satellites currently equipped with sensors suited for fireball detections have military purposes. Since these do not include the scientific study of meteor events, these data are usually discarded and are lost. Even recorded events, moreover, when not discarded, are usually not made public, being included in the records of classified activities.

In cases of satellites devoted to civilian activities, like systematic monitoring of large areas of the Earth for various purposes, what commonly happens in practice is that data reduction pipelines are conceived to record events having much longer time scales with respect to meteoric events. For instance, satellites aimed at monitoring the long-time evolution of different ecological environments, are not supposed to record events with typical durations of a couple of seconds. As a consequence, data showing sudden changes like meteors or fireballs are automatically discarded as a source of high frequency noise.

Meteor and fireball observations are important to derive important physical information on the population of meteoroids orbiting in the vicinity of the Earth. After decades of ground-based activities, which have been able to obtain the best conceivable results from available detectors, the times seem now finally mature to plan the development of a new generation of dedicated, space-based observing facilities. We are going to explain why we think that the proposed JEM-Euso mission is an excellent candidate to be the first working example of space-based platform producing important data for meteor and bolide studies.

We want also to note that, apart from purely scientific issues, a space-based system for fireball surveillance could have also some more immediately practical purposes. It is known, in fact, that the clouds of dust released by these events can be a hazard for aircraft, and moreover the impact of a sufficiently big meteorite in an ocean or sea can produce a dangerous Tsunami wave. For these and other reasons, a prompt detection of these events could be of the highest importance also for mitigation of possible danger for human beings in particular circumstances.

4. The proposed JEM-Euso mission

JEM-Euso is a project to accommodate aboard the Japanese Experiment Module (JEM) of the International Space Station (ISS) an instrument, (Extreme Universe Space Observatory), aimed at detecting cosmic rays of extremely high energies. The idea is to have a detector monitoring downward the Earth from an height of about 400 km, in order to use a large volume of the Earth's atmosphere as a giant cosmic ray detector to study the most energetic particles coming from the Universe. This project is a worldwide collaborating effort of 75 research teams from 13 countries.

According to the mission design, JEM-EUSO will observe extremely energetic cosmic rays by detecting and recording the fluorescence signal produced during their passage through the atmosphere. The main scientific objective is to do cutting-edge studies in fundamental physics and astrophysics by detecting events produced by particles having energies above 10^{20} eV, so extending, with a significant statistical evidence, the measurement of the energy spectrum of the cosmic radiation beyond the Greisen-Zatsepin-Kuzmin (GZK) cut-off. Using the atmosphere as a giant detector, JEM-EUSO will also perform observations of extremely high energy neutrinos, then opening a new field of high-energy neutrino astrophysics.

The JEM-EUSO payload consists of a UV telescope in the 2-meters class, assisted by an atmosphere monitoring device and controlled by a calibration system. The telescope is, in practical terms, a fast, large-aperture and large field-of-view digital camera, working at near-UV wavelengths (330 ÷ 400 nm), with single photon counting capability. The collection of photons by the optics requires:

- Field of view (FOV) larger than ±30°.
- Entrance Pupil Diameter (EPD) on axis: 2.3m.
- Focal number $f/\#$ 1.25
- Spot size smaller than the pixel size of the focal surface detector.

The large FOV indicated above is required to maximize atmosphere coverage, in order to enhance as much as possible the statistics of detected events. Moreover, the pupil aperture must be as big as possible in order to detect faint fluorescence signals and Cherenkov photons with sufficient S/N. In addition, the system must be as fast as possible (requiring small $f/\#$) in order to have an acceptable focal surface in terms of dimensions and weight.

According to current design, with a FOV aperture of ±30°, the optics focuses the incident UV light onto the focal surface with a spatial resolution of 0.07°. The focal surface detector is composed by a grid of $\sim$ 5000 multi-anode photomultipliers, which convert the energy of the incoming photons into electric pulses with duration of 10 ns. The electronics counts-up the number of the electric pulses in time periods of 2.5 μs and records them. Whenever a signal pattern coming from an extremely energetic particle event is found, the electronics issues a trigger signal and transmits all the useful data to the ground operation centre, tracking back the image information stored in the memory.

In addition to its primary scientific objective, JEM-EUSO will contribute to the investigation of a variety of phenomena occurring in the Earth's atmosphere, including also the detection of meteors and fireballs over a wide range of apparent brightness. The study of atmospheric phenomena must not be considered as a simple by-product of the adopted strategy of cosmic rays detection, but it will be a fundamental task of the mission, due to the need of determining the environment conditions characterizing each high-energy event detection, in order to interpret the details of the detection taking into account effects of extinction and reflection experienced by the signal. According to current estimates, only 30% of the events will be detected in conditions of clear sky.

For what concerns atmosphere monitoring, the payload will include an IR camera and a Lidar (light detection and ranging) using an ultraviolet laser to observe the conditions of the atmosphere in the FOV of the telescope, in order to determine effective observation time, and increase the reliability of event detection near the instrumental energy threshold. The role of the Lidar is to observe the condition of clouds in several points of the JEM-EUSO FOV, and to calibrate with high accuracy the transformation table between altitude of cloud tops and their temperature, obtained by the analysis of the onboard IR camera images. Since the wavelength of the Lidar laser is 355 nm, the telescope itself will be used as the Lidar receiver unit.

JEM-EUSO has been designed to operate for more than 3 years aboard the International Space Station, orbiting around the Earth every 90 minutes at an altitude of about 400 km.

5. Current activities and problems

Meteors and fireballs have been in the past, and still are commonly, observed mostly at visible wavelengths. However, we have seen that in these events the meteoroid material is heated up to very high temperatures, thus it is expected to emit significantly at UV wavelengths. In particular, the emission of the ionized material along the meteoroid track is expected to include spectral lines in the UV spectral region. Therefore, space-based sensors optimized to work at UV wavelengths can be very efficient to record these events, and the current design of JEM-Euso suits the needs for space-based detection of meteors and fireballs.

The first step in our analysis of the possible application of JEM-Euso to meteor and fireball studies consists of an assessment of the compatibility of meteor observations with the overall mission design, taking into account how the onboard electronics is supposed to work. It must be noted that meteor events can be classified as "slow" events in the framework of JEM-Euso operations. In the case of cosmic rays events, in fact, typical durations of the events are between 50 μs and 1 ms, and the corresponding timescale for data sampling will be around 2.5 μs. Conversely, in the case of meteors, which are events having typical timescales of the order of one second, acquiring data every 2.5μs for the duration of the phenomenon is impossible because this would block the entire data acquisition of the instrument. A special trigger for meteors observation is therefore needed. Another difference between meteor and cosmic rays events is the range of possible apparent brightness. In the case of fireballs, the apparent brightness may well reach extremely high values. Based on the above considerations, we are led to design a separate observation mode for meteors, taking into account the need of reducing the photomultiplier efficiency and the data acquisition rate in order to preserve the integrity of the detectors and to make possible data acquisition and transmission to the Earth. In this respect, we have seen that data sampling frequencies of the order of 10^{-3} s are fully acceptable.

The conversion between apparent brightness expressed in UV magnitudes and the corresponding number of expected photo-electrons per GTU is known. This allows us to make predictions about the flux of photo-electrons produced by meteor events of different magnitudes. In particular, we may expect that, taking into account the overall instrumental sensitivity, the faintest magnitude limit for detection of meteors should be about apparent magnitude 7. In ideal conditions (dark sky) the corresponding frequency might reach 1 event per second in the JEM-Euso FOV. We do not give an upper limit in apparent brightness in our analysis, knowing *a priori* that very luminous events will be increasingly more rare, but that these events will be also the most interesting ones for scientific purposes, and also the most easily observable ones in terms of JEM-Euso observing strategy. It is clear, in fact, that the fraction of time that will be mostly devoted to meteor observations will be that corresponding to non-ideal observing conditions for cosmic rays detection (sky non entirely dark due to the presence of the Moon, or large illuminated areas on the ground, corresponding to big cities). In these non-ideal conditions, the observation of bright meteors and possible fireballs will be anyway possible and will be an excellent exploitation of the JEM-Euso duty cycle.

Our preliminary work has so far consisted of making simulations of meteor phenomena, in order to simulate how such events can be processed by an *ad hoc* trigger strategy, and to assess also full compatibility with the trigger strategy designed for cosmic ray data processing. In practical terms, we are exploring the possible strategy of recording a frame of 1 GTU (an integration of 2.5 μs of signal) every 10 ms for the duration of the event, to verify whether the collected frames are sufficient to reconstruct the meteor profile.

For this purpose, a simple numerical simulator has been developed. It consists of an algorithm which computes the signals emitted by meteor events in a wide variety of possible situations. The input parameters of the simulator include the meteor beginning height, velocity vector, event duration, absolute magnitude (taking into account that, by definition, the absolute magnitude of a meteor is defined as the apparent magnitude that would be measured if the meteor was located in the zenith at a standard height of 100 Km), initial position vector with respect to both the ground and the ISS, lightcurve profile (including the possibility of secondary light bursts), and frequency of signal recording. The computed light flux reaching the Jem-Euso focal surface every time step is directly given in photo-electrons/GPU. The simulated observations allow us to perform an analysis of the slow-data processing pipeline, taking into account gain switches, *etc.*, in order to develop the best strategy for the observation of these events. Moreover, the simulator allows us to produce random meteors (characterized by sets of reasonable parameters), and

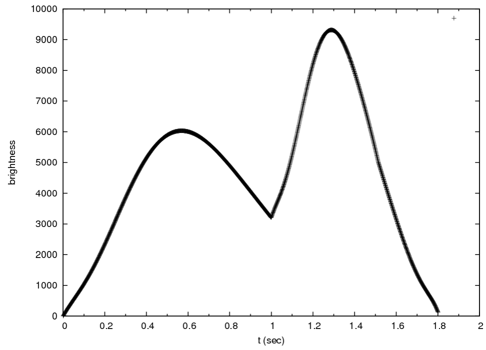

Fig. 1. Example of a simulated meteor event as seen from a detector aboard the ISS. In this case, a secondary brightness burst occurring about one second after the beginning of the event, produces a secondary brightness surge superimposed to the original signal. In this plot, the brightness is expressed in photo-electrons/GTU.

this is useful to carry out blind tests. An example of synthetic meteor lightcurve produced by the simulator is given in Fig. 1. This simulation work is still currently in progress, but the preliminary results look encouraging and suggest that the observation of meteors and fireballs from JEM-Euso should be feasible and not in conflict with the primary objectives of the mission.

There is, however, a problem which deserves careful attention. One major difference between the observation of very energetic cosmic rays and meteor events is that, in the former case, the *velocity* of the propagating signal is known at every instant, being simply equal to the speed of light. In this case, the three-dimensional trajectory of the particles can be reconstructed from the recorded projected trajectory in the JEM-Euso focal plane.

In the case of meteors and fireballs, as opposite, no *a priori* information about the speed of the impactor is available. In these conditions, the availability of one single projected trajectory, recorded by the JEM-Euso telescope, is not sufficient to derive the three-dimensional trajectory of the body. It is a well known fact in meteor science, that to derive the trajectory, it is necessary to have at disposal simultaneous observations carried out by different, well-separated observers. This is the reason for establishing large networks of ground-based meteor observatories.

In the case that JEM-Euso works alone, we will have the possibility to derive information on the magnitude frequency of the events, and possibly about some clues on the physics of the ablation process based on analyzes of the collected lightcurves. On the other hand, no observation about the original orbits of the meteors nor on the likely site of impact of meteorites delivered by energetic fireball events, will be available. For these reasons, we are currently taking contacts with the scientists in charge of the ground-based meteor observation networks, in order to make all possible effort in order to have important support from ground-based observers. Although preliminary contacts have evidenced that the possibility of such kind of collaboration should easily develop due to the willingness of all the actors in this game, it remains the fact that the orbital speed of the ISS makes any apparition of JEM-Euso over any given terrestrial region a very short event. It is therefore easy to predict a low duty-cycle in terms of capability of deriving meteor orbits through the simultaneous detection of events from the ISS and from the ground. This problem will certainly deserve further analysis.

6. Conclusions

We do not know yet whether JEM-Euso will be eventually launched, although it is clear that a strong international community of scientists working in different disciplines are strongly promoting this mission and are working actively for its success. What we can say is that we do think that JEM-Euso has the potential to become the long-sought first example of a space platform devoted, at least partially, to the detection of meteors and fireballs. Preliminary simulations confirm that the mission design is fully compatible with the needs of meteor studies. The problem of the reconstruction of the three-dimensional trajectories of the objects looks as the most important scientific limit in the current configuration. Apart from the help of ground-based observers, we are also exploring the possibility to use the motion of the ISS itself as a tool to have some chance to make some triangulation, at least in cases in which the meteor signal might be sufficiently persistent, perhaps taking profit of the on-board IR camera, too.

In any case, we strongly believe that the beginning of a new era of meteor observations from space is imminent and this will produce results of extreme importance for planetary sciences.

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