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Near-Earth space hazards and their detection
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A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS), titled "Near-Earth space hazards and their detection", was held on 27 March 2013 at the conference hall of the Lebedev Physical Institute, RAS.

The agenda posted on the website of the Physical Sciences Division, RAS, www.gpad.ac.ru, included the following reports:

(1) **Emel'yanenko V V, Shustov B M** (Institute of Astronomy, RAS, Moscow) "The Chelyabinsk event and the asteroid-comet hazard";

(2) **Chugai N N** (Institute of Astronomy, RAS, Moscow) "A physical model of the Chelyabinsk event";

(3) **Lipunov V M** (Lomonosov Moscow State University, Sternberg Astronomical Institute, Moscow) "MASTER global network of optical monitoring";

(4) **Beskin G M** (Special Astrophysical Observatory, RAS, Arkhyz, Karachai-Cirkassian Republic) "Wide-field optical monitoring systems with subsecond time resolution for the detection and study of cosmic threats".

The expanded papers written on the base of oral reports 1 and 4 are given below.

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The Chelyabinsk event and the asteroid-comet hazard

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1. Introduction

In the morning of 15 February 2013, at about 9 h 20 min local time, near the city of Chelyabinsk (Russia) an explosion of large meteoroid entering Earth's atmosphere occurred. The cosmic body had not been detected by any monitoring facility before it entered the atmosphere, which it did at an angle of about 15 degrees to the horizon. Starting from this moment, the body's further passage through the atmosphere was accompanied by phenomena detected by different observational facilities. The brightest phenomenon associated with the interaction of the extraterrestrial body with the atmosphere included a strong glow (also known as bolide), which was observed over a large territory. The bolide was registered by video cameras over a long time interval (up to 16 s). The brightness of the bolide rapidly increased and ended with a powerful flash. According to eyewitnesses, the brightness of the flash significantly exceeded that of the Sun, and heat was felt. In several minutes, a powerful shock wave arrived. Some people were injured due to the shock (mainly because of knocked out windows). According to the Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters (EMERCOM of Russia or MChS in *Russ. abbr.*), 1613 persons requested medical assistance. The shock caused damage to buildings (broken windows, torn down false ceilings, broken window frames, etc.). The material damage was preliminary estimated to be from 400 mln to one billion rubles.

In the present report, we briefly describe observational data on the Chelyabinsk event and provide the initial results of the scientific analysis of these data. Special attention is given to the determination of the physical and dynamical characteristics of the celestial body. We also discuss the meaning of the Chelyabinsk event in connection with the comet and asteroid threats to Earth.

2. Observational data on the Chelyabinsk event

The event of 15.02.2013 (the Chelyabinsk bolide) is prominent among other cosmic bodies that have entered Earth's atmosphere due to a large variety of observational facts. These include data obtained by modern facilities for remote observations: registration of emission by satellites, registration of many infrasonic and seismic signals, and satellite and ground-based detections of the dust trail in the atmosphere. However, in our opinion, the most valuable are observations made in the immediate vicinity of the event in the Chelyabinsk region. To collect these data, the Institute of Astronomy of RAS (INASAN) and the Institute of Geosphere Dynamics of RAS (IGD RAS) organized an expedition to the Chelyabinsk region, which took place from 9 to 26 March 2013. The team consisted of E E Biryukov (South-Ural State University), D O Glazachev (IGD RAS), P Jenniskens (The Center for SETI Research (SETI Institute), USA), V V Emel'yanenko (INASAN), A P Kartashova (INASAN), O P Popova (IGD RAS), and S A Khaibrakhmanov (Chelyabinsk State University). The main goals of the expedition included: (a) astronomically linking video records of the Chelyabinsk event obtained mainly by car video recorders and cameras;

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(b) obtaining information about the Chelyabinsk event from official sources, and (c) collecting eyewitnesses' testimonies in various local towns and settlements.

The video records of the Chelyabinsk bolide have been used first and foremost to determine the trajectory of the cosmic body in the atmosphere (and then to determine its extra-atmospheric orbit), as well as the important physical details of the meteoroid's flight in the atmosphere, including the light curve characterizing the change in a radiant energy release in time, the structure of the trail highlighting the details of the body's destruction, etc. Presently, we have at our disposal more than 150 video records of the Chelyabinsk event obtained from the Internet and via direct appeal of the Space Threats expert working group of the Space Council of RAS to eyewitnesses, although not all of the records are appropriate for scientific analysis. The expedition took oriented surveys of the stellar sky from the same spots from which the meteor snapshots were made. Clearly, the restricted time did not allowed us to carry out the astronomical linking of all the video records, which are interesting from the viewpoint of determining the bolide orbit (including obstacles posed by weather conditions). However, the obtained data seem to be very valuable, in particular, due to the astronomical linking that was done of video records taken from remote sites (from Beloretsk to Verkhnyaya Pyshma).

During the expedition, we managed to obtain important information from services of the Chelyabinsk region government, the Chelyabinsk Regional Directorate of EMERCOM of Russia, and other official bodies about the destruction zone, the number of damaged windows, the number of injures, etc. Of great scientific value are records from outdoor surveillance cameras synchronized in time and located, besides in Chelyabinsk, in Zlatoust, Kurgan, Magnitogorsk, Miass, and Chebarkul. Of equal importance is evidence provided by numerous eyewitnesses of the event. The participants in the expedition visited about 50 settlements in which data on destruction, visible impressions of the bolide phenomenon, and possible sites of meteorite material precipitation were collected. The greatest destruction was registered in the direction normal to the body's trajectory, suggesting a cylindrical character of the shock wave propagation.

The expedition was not aimed at collecting meteorite material that fell to the ground. First, this task was pursued by earlier expeditions headed by V I Grokhovsky (Ural Federal University) and D D Badyukov [V I Vernadsky Institute of Geochemistry and Analytical Chemistry (GEOKhI) of RAS]. Second, by the time our expedition began, a half-meter layer of snow had fallen which covered traces of meteorite matter remnants. We note only that most of the meteorite pieces were found between the villages of Aleksandrovka and Deputatskoe. According to data from the Meteoritic Laboratory of GEOKhI RAS (http://www.meteorites.ru/menu/press/yuzhnouralsky2013.php), the Chelyabinsk meteorite was an ordinary type LL5 chondrite.

So far, no big fragments of the meteorite have been found (the largest piece has, according to V I Grokhovsky, a mass of 1.8 kg). Discussion continues on the possibility that a large fragment fell into Lake Chebarkul, forming an ice-hole 6–8 m in diameter, which is seen in a snapshot taken by E O Kalinin from an airplane (Fig. 1). However, despite active searching, big fragments have not been found in water so far.

Interesting also are lunules less than 15–20 cm in size discovered by E O Kalinin from an airplane on the surface of the ice of lakes Argayash, Dyvankul, and Etkul (Fig. 2), which were absent before the Chelyabinsk event. No small remnants have been discovered near these sites.

Figure 1. Unfrozen patch of water in the midst of ice on Lake Chebarkul, possibly created by a large fragment of the Chelyabinsk meteorite (photo by E O Kalinin, 16.02.2013).

Figure 2. Lunule on the surface of the ice of Lake Etkul, possibly formed by a fragment of the Chelyabinsk meteorite (photo by E O Kalinin, 17.02.2013).

3. First results of the studies of Chelyabinsk event

Let us briefly describe the physical and dynamical characteristics of the cosmic body and details of the physical picture of its traveling through Earth's atmosphere, obtained to date from the analysis of observational data. A more detailed description of the methods used in this study is presented in paper [1].

The analysis of the light curve of the bolide revealed that the main radiant energy release lasted for about 6 s. During this time interval, several flashes were registered, one of which was significantly brighter (the main flash) and occurred about 11 s after the appearance of the meteorite trail. The duration of this outburst was around 2.5 s, and during this time at least 70% of the total radiant energy of the bolide was released. It is natural to connect the brightest flash with the main phase of the meteoroid's destruction. Thus, the explosion (destruction of the body accompanied by a powerful energy release due to interaction with the atmosphere) was not point-like, as for instance in the explosion of a bomb, but was distributed along a long part (several dozen kilometers) of the trajectory. This naturally explains (see Section 2) the cylindrical character of the shock wave observed.

The processing of video records showed that the minimum time delay (77 s) of the shock wave relative to the main light flash was observed in Pervomaisky settlement. Near this village, the destruction of the body occurred at an altitude of 23–24 km. The analysis of video shots revealed that the maximum of the flash brightness, corresponding to the maximum of the light curve, was reached by the time the cosmic body was at an altitude of 28–30 km, in 20 km east of Pervomaisky.

From a comparison of the energy estimates taken from the excessive air pressure at which window glass was broken in the city of Chelyabinsk, infrasonic data, and light recording from satellites, which was carried out in paper [1], the conclusion was made that the kinetic energy of the cosmic body reached approximately 300–500 kt of trinitrotoluene (TNT) equivalent. With a velocity of 18.8 km s^{-1} and density of 3.2 g cm^{-3}, the diameter of the body at the time of entrance into the atmosphere ranged from 16 to 19 m.

Here, we do not discuss in detail the orbit of the cosmic body before its impact with Earth, postponing this question to the end of the processing of all available observations and their astronomical linking. Note only that, according to telegram [2] and our preliminary estimates given in Ref. [1], this asteroid belongs to the Apollo type group.

4. Chelyabinsk event as an illustration of the comet and asteroid threat problem

The Chelyabinsk event has also been broadly discussed in the context of the so-called comet and asteroid threat (CAT) problem, i.e., the danger of Earth encountering small bodies in the Solar System (asteroids and comets), which can result in serious damage to the planet, or even destruction of the human race. As noted in Refs [3, 4], the impact with extraterrestrial bodies 50–500 m in size, occurring on the time scale of the existence of the human race (*Homo sapiens*) of about 200,000 years, is the main danger of CAT. In this sense, the Chelyabinsk event does not relate to the CAT problem, since this meteoroid is not classified as a dangerous celestial body (DSB). The damage due to the fall of the Chelyabinsk meteorite is not very large, although in this case we were lucky: if the meteoroid trajectory had been less tilted to the atmosphere, the consequences of the explosion could have been much more catastrophic. Moreover, if the size of the body had been 50 m or more, there would have been no chances of a good outcome. The interested reader can find more discussion of the meteorite danger in review [5].

Nevertheless, the Chelyabinsk event represents a compelling illustration of the reality of CAT. In this connection, many questions have arisen in society, which are related to earlier discoveries of celestial bodies similar to the Chelyabinsk one and the possibility of taking preventive measures to reduce the risk. Without delving into the details here, we wish to give a short commentary.

Detection. History knows only one case where a meteoroid was observed for a relatively long time (20 h) in advance of its entering Earth's atmosphere [6]. The meteoroid was 3–5 m in diameter, and there can be several entries of such bodies into Earth's atmosphere every year. This means that the meteoroid referred to as 2008 TC3 was spuriously discovered, albeit in the course of a systematic survey. At large distances, such bodies with a size of less than 20 m cannot be discovered due to the limiting power of modern survey telescopes (see paper [7]). At small distances, the difficulty in discovering such bodies is due to the too short time before their entering Earth's atmosphere.

As for the Chelyabinsk meteoroid, it could not have been discovered using *any* of the currently available observation facilities. It could not have been observed in the optical range because it approached Earth from the side of the Sun. At the time it entered Earth's atmosphere, the angular distance from the Sun was as small as 15 degrees. Such an object cannot be observed either from the ground or by a space telescope on a near-Earth orbit, since the critical value of the avoidance angle (the angular distance to the Sun within which it is impossible to point a telescope for fear of unrecoverable damage) amounts to 30–35 degrees (according to different space projects). Radio facilities of the near-cosmos control cannot be effective either. The reasons are rather simple: first, the limiting action radius for such systems is 5–10 thousand km, which for DSB velocities of 20–30 km s^{-1} implies an impact point time of less than a few minutes (which is too short to react), and second, such facilities cannot simultaneously observe the target in such a broad range of velocities (due to frequency channel limitations). An outcome presently discussed is the construction of fast middle-aperture detectors, both ground-based [see, for example, the description of the ATLAS system (Asteroid Terrestrial-impact LAst System) at http://www.ifa.hawaii.edu/info/press-release/ATLAS/] and space-based. A proposal to build in Russia a system for preliminary detection of relatively large cosmic bodies with a size of more than 50 m (with a lead time of at least one month) and the detection of meteoroids and space garbage fragments in the near-Earth space is described in detail in Ref. [8], where an outline sketch of a national (federal) program to counteract cosmic threats is discussed.

Countermeasures. The high velocities of meteoroids and short time of their arrival exclude the engagement of rocket defense facilities. The use of other facilities (for example, powerful laser weapons) with sufficient power to destruct such massive bodies has so far been considered as research and development projects. The only reasonable means of decreasing the potential damage after recognizing the danger of a close impact (on the time scale of a few hours) includes the use of EMERCOM technologies, alerting and evacuating population to a safe area, switching off dangerous installations, stopping dangerous industries, etc. Of course, it is necessary to continue fundamental research on different aspects of influencing dangerous cosmic bodies. In this connection, studies of natural encounters of cosmic bodies (see, for example, review [9]), as well as of the impact of small celestial bodies with spacecraft (see, for example, review [10]) take on a great significance.

5. Conclusion

(1) From the astronomical point of view, the Chelyabinsk event demonstrates the typical case of asteroid entrance into Earth's atmosphere. The peculiarity of this event is due to its occurring, for the first time in modern history, in a densely populated area, which led to noticeable destruction and was detected by numerous observational facilities, including video cameras.

(2) The Chelyabinsk event is a compelling illustration of the reality of the asteroid and comet threats. It is necessary to develop systems for the advance detection of small dangerous cosmic bodies. It is a serious scientific and technological issue, and Russia cannot stay away from the general trend.

(3) For effective research, a federal level program is needed. The conceptual design of such a program is presented in Ref. [8].

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Wide-field subsecond temporal resolution optical monitoring systems for the detection and study of cosmic hazards

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1. Introduction

In the present paper, we discuss the possibility of using multi-objective optical telescopes equipped with detectors with high time resolution to discover and study rapidly moving cosmic objects of both natural and artificial origins. Two types of instruments (with six and nine channels) are considered here, which include the standard high-aperture objectives with small diameters (70 mm), panoramic detectors with high time resolution, and equatorial mounts. The instruments function in two regimes: the monitoring mode (with fields of view of 600 and 900 square degrees), and the follow-up mode (with a field of view of 100 square degrees) in which all objectives observe one field with a rapidly moving celestial object detected by monitoring. The re-pointing of objectives in a few fractions of a second is achieved by turning the flat mirrors mounted in front of the objectives, and color and polarization measurements are carried out using a set of filters and polaroids. We describe the features of the construction of prototypes of the devices, their characteristics, and the parameters of detectable dangerous objects. Also discussed are prospects for the development of such systems, in particular, the possibility of constructing one complex including several hundred 40-cm telescopes with a 1-square-degree field of view.

The search for and study of optical objects and phenomena rapidly variable (transient) in time and space relate to a fairly new field of modern astronomy. This problem was first clearly formulated by H Bondi in 1970 [1], who noted the need to discover and follow up nonstationary objects with unknown *a priori* localization. In such observations, very wide-field instruments (with a field of view of several hundred square degrees) equipped with panoramic detectors with at least sub-second time resolution must be utilized. The latter requirement is due to the short durations (down to 0.01 s) of transients (UV Ceti star type flares, gamma-ray bursts (GRBs), rising fronts of supernova and nova explosions, etc.) and/or the high velocities (up to several dozen degrees per second) of their proper motion (satellites, space debris, meteors, and bolides) [2].

Table 1 lists optical transients classified by their localization and duration. As examples, we note two — 'opposite' in some sense — classes of optical transients: natural and artificial objects which can be dangerous to the human race, and flashes associated with cosmic gamma-ray bursts.

Clearly, a deep detection limit (large-diameter objective) in combination with a wide field of view (short focus) and high time resolution (small size of the detector) are intrinsically contradicting; therefore, it is necessary to seek a reasonable compromise when choosing these parameters. This compromise seems to be found in the project for a wide-field camera which has a relatively small objective, an image intensifier for effective focus shortening, and a fast, low-noise CCD (charge coupling device) detector [2]. The prototype of such an instrument, FAVOR (FAst Variability Optical Registration), commissioned in 2003, is installed near

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