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Small bodies of the Solar system—scientific challenges and practical aspects

B. Shustov

Institute of Astronomy of the Russian Academy of Sciences,
Pyatnitskaya 48, Moscow, 119017 Russia

Abstract. The study of small bodies of the Solar system provides the key to understanding the processes of its formation and evolution. Basic science here is closely related to the applied aspects. First of all, this is true in relation to Near-Earth Objects (NEOs). The brief overview focuses on the discussion of such links. In particular, the following two topics connecting fundamental and practical issues are considered: origin, characteritics, and evolution of the NEO population ⟷ the problem of asteroid-comet hazard; meteoroids of both cometary and asteroid origin ⟷ safety of space activities in near-Earth space. The issues of coordination of research on small bodies topic both at the domestic and international levels are briefly discussed too. Special attention is paid to the prospects for coordinating research work on small bodies within the framework of the federal project “Mlechny Put” (Milky Way).

Keywords: small bodies of the Solar system, Near-Earth Objects, planetary defense, meteoroids, safety of space activities

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1 Introduction

Resolution B5 of the General Assembly of the IAU[1] specifies concept of "small bodies of the Solar system". These are objects that, by their characteristics, cannot be attributed either to dwarf planets or to planets or their moons. It is explained that this group includes most of the asteroids of the Solar system, most of the trans-Neptunian objects, comets and other bodies.

Meteoroids and interplanetary dust also belong to the small bodies of the Solar system. Until recently, there was no clear criterion for separating the concepts of "asteroid" and "meteoroid", "interplanetary dust". In 2017 the IAU F1 Commission adopted recommendations on the use of the terms "meteoroid" and "interplanetary dust",[2] allowing for a unambiguous use of these terms. According to these recommendations:

- meteoroids—solid objects ranging in size from about 30 microns to 1 m, moving in interplanetary space;
- interplanetary dust—solid interplanetary objects up to 30 microns in size.

It follows from these definitions that asteroids (and comet nuclei) are solids larger than 1 m.

The topic of small bodies is a gigantic field of scientific research. As noted in Jacobson et al. (2021), "small bodies are time-capsules of different eras of the Solar system history from the most primitive materials within the Solar system to evolved pieces of larger bodies".

Small bodies carry information about all corners of the Solar system. We get some of this information by studying meteorites, but although our meteorite collections are an important source of knowledge about the history of the Solar system, they provide an incomplete understanding of the properties and fate of solids in space. Growing attention is being paid to the study of small bodies both by methods of ground-based astronomy and using spacecraft.

In addition to basic science, the small bodies of the Solar system are of great practical interest. This is also very true for near-Earth objects (NEOs). This brief overview focuses on discussing such relationships. In particular, the following topics linking fundamental and practical issues are considered:

- The origin and evolution of the NEO population ⟷ the problem of asteroid-comet hazard (Section 2).
- Meteoroids of both cometary and asteroidal origin ⟷ safety of space activities in near-Earth space (Section 3).

[1] https://www.iau.org/static/resolutions/Resolution_GA26-5-6.pdf—accessed: 14 July 2024.

[2] https://www.iau.org/static/science/scientific_bodies/commissions/f1/meteordefinitions_approved.pdf—accessed: 14 July 2024.

The issues of coordination of research on small bodies at the domestic and international levels are briefly discussed too. Special attention is paid to the prospects for coordinating the research of small bodies within the framework of the federal project ”Milky Way” (Section 4).

2 NEOs and planetary defense

Near-Earth objects (NEOs) are asteroids (NEAs) and comets (NECs) with a perihelion distance $q < 1.3$ AU. The subset of NEOs—Potentially hazardous objects (PHOs)—are bodies whose orbits can approach the Earth's orbit to a minimum orbit intersection distance (MOID) of no more than 0.05 AU. In the literature this (dynamic) definition of PHOs was added by the requirement that the absolute asteroid magnitude of the body H should not exceed 22.0.[3] With some average value of the asteroid albedo $A = 0.15$, the size of a spherical body with $H = 22$ is estimated at approximately 140 m according to the formula $D = 10^{3.1236-0.5\log A-0.2H}$ (Harris and Harris 1997). Currently, the critical size limit is being revised and reduced from 140 m to at least 50 m (the size of the Tunguska body), and more recently even to ~ 10 m (the practical lower limit confirmed by the Chelyabinsk event).

The concept of NEO is closely related to the concept of asteroid-comet hazard (ACH aka NEO problem). ACH is a hazard of possible collisions of small bodies with the Earth causing major damage to the population of the planet up to the destruction of civilization. Regarding the problem of near-Earth objects, astronomy as a fundamental science is expected to answer the following questions:

- Number of NEOs in the Solar system.
- Characteristics of NEOs important for planetary defense purposes.
- Frequency of collisions of NEOs with the Earth.
- How to construct an efiicient system for detecting and monitoring hazardous space objects.

Very brief answers to some of these questions can be found in the diagram shown in Fig. 1 taken from the NASA's document “National Preparedness Strategy and Action Plan for Near-Earth Object Hazards and Planetary Defense”.[4] Of course, this diagram shows only some “average” estimates. First of all, this concerns the distribution of NEOs by size.

[3] https://cneos.jpl.nasa.gov/about/neo_groups.html—accessed: 24 July 2024.
[4] www.whitehouse.gov/wp-content/uploads/2023/04/2023-NSTC-National-Preparedness-Strategy-and-Action-Plan-for-Near-Earth-Object-Hazards-and-Planetary-Defense.pdf—accessed: 24 July 2024.

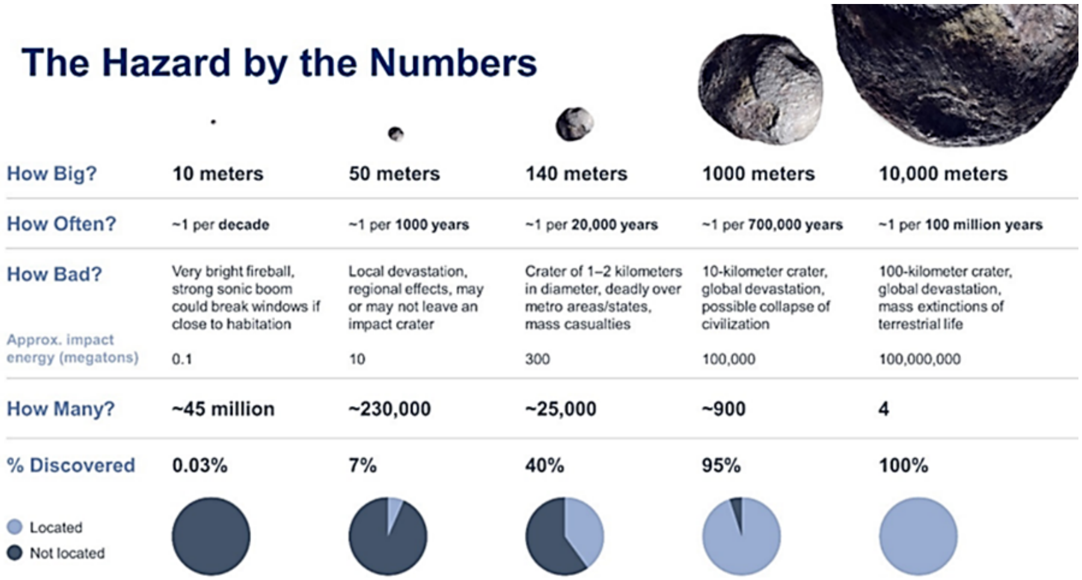

Fig. 1. NEO size, frequency of Earth-impact, and hazard

It is customary to illustrate the number of detected NEOs and detection completeness degree with a well-known and permanently updated diagram[5] (Fig. 2). The inset in Fig. 2 shows the number of potentially hazardous asteroids and comets. Obviously, the share of comets in the total number of NEOs is very small, and the statistics of detected NEOs well represents the complete statistics of NEOs.

The completeness of NEO detection is increasing and it can be assumed that by now the completeness of detection of bodies larger than ~ 1 km (more precisely 0.7 km) has been achieved at a level of ~ 90 – 95%. However the NEO problem relates to collisions with bodies ranging in size from decameters to half a kilometer. Larger bodies collide with the Earth so rarely that practical interest is not expressed here. For smaller near-Earth objects, observations are not complete enough, so different models are used. The models give a very large spread, the larger the smaller the body.

Figure 3 represents cumulative distribution of known NEOs by H (also by diameter D). The diagram is constructed using the model of Granvik et al. (2018) (marked as “This work”) and models presented in the works of other authors. The identification of the mass spectrum of small asteroids remains a serious scientific challenge.

[5] https://cneos.jpl.nasa.gov/stats/totals.html—accessed: 24 July 2024.

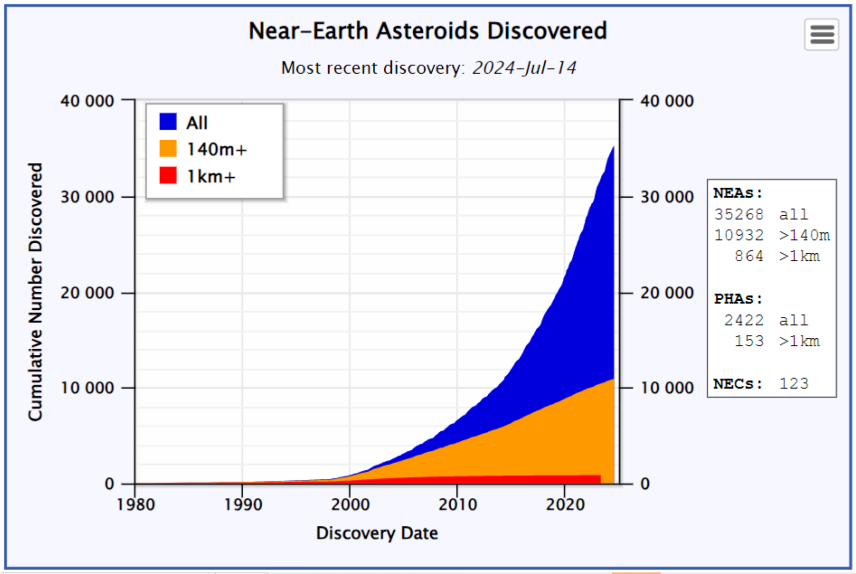

Fig. 2. Near-Earth asteroid detection statistics.

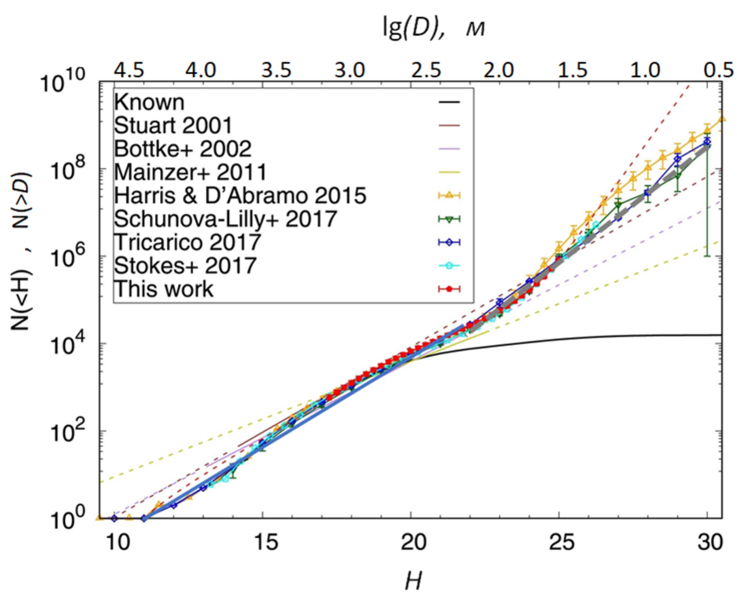

Fig. 3. The observed cumulative distribution of NEOs by H (also by diameter D) according to the model of Granvik et al. (2018) (marked as 'This work'), and models presented by other authors.

Characterisation of NEOs is vitally important for proper planning of planetary defense activities. Barbee et al. (2020) presented a high-level notional priority of NEO characteristics for measurement for planetary defense purposes. These are (in order of decreasing notional priority): precise orbit; mass; binarity; shape (taking into account the mass, the bulk density can be determined); strength; internal structure (including porosity); mineral composition; and detailed surface topology.

The major practical issues of the NEO problem are:

1. Detection (identifying) of all dangerous bodies and revealing their properties.
2. Risk assessment in a case of a specific collision threat.
3. Counteraction and mitigation (damage reduction).

The first problem and a large part of the second problem are the responsibility of astronomers. Obviously, the first problem has the highest priority.

To select the most effective instruments and observation strategies for NEO detection, it is important to determine the input requirements for such instruments. The problem of NEO detection can be solved only with the help of optical and infrared ground-based and/or space-based telescopes. As practice shows, the creation of a universal instument (telescope) for the timely detection of NEOs of all sizes (from 10 m and more) is hardly possible. Neither the large working telescopes (like the famous Pan-STARRS, the "Fly eye" NEOSTEL telescope (Marchiori et al. 2022), nor the future giant ($\omega = 3°$, $\varnothing 8$ m) ground-based telescope LSST (Ivezić et al. 2019), nor the space infrared observatory NEO Surveyor (Mainzer et al. 2023) are a panacea.

Shustov et al. (2013) proposed a two-mode structure for constructing a ground-based NEO detection system:

<u>Long-range detection mode (NEO size $\gtrsim 50$ m)</u>

- Lead time ~ 30 days (i.e., first detection time > 35 days).
- Time for all-sky survey (cadence) $\lesssim 5$ days.
- The main assets are telescopes of the visible ranges. It is necessary to work at the limit of 23^{m} V, which requires for wide-angle ($\omega > 1°$) large-aperture ($\varnothing \sim 1$ m) telescopes.

<u>Near-field detection mode (NEO size $\gtrsim 10$ m)</u>

- Lead time ~ 1 day.
- The time for all-sky survey $\lesssim 1$ hour.
- The main element is an expanded network of wide-angle ($\omega > 4°$) low-aperture ($\varnothing \lesssim 0.5$ m) telescopes of the visible range. It is necessary to work at the limit of 17^{m} V.

There are networks that can be classified as middle class. For example, ATLAS, the Asteroid Terrestrial-impact Last Alert System of 50-cm telescopes, is a robotic astronomical survey and early warning system optimized for detecting smaller near-Earth objects a few weeks to days before they impact the Earth (Tonry et al. 2018). However, such networks still do not have sufficient cadence to detect extremely small and close NEOs.

In recent years robotic observation pipelines for small bodies in the Solar system based on open-source software and commercially available telescope hardware are becoming popular (see, e.g., Hoffmann et al. 2022). There is a tendency to create multi-aperture robotic systems for the near-field detection mode. An example is the Mini-MegaTORTORA (MMT-9) instument (Karpov et al. 2016), which is successfully used at SAO RAS. The aperture of the telescopes is too small, but the version with an aperture of 30 cm, which is being prepared for implementation, will already be a sufficiently powerful and at the same time very economical instrument.

In Shustov et al. (2015) it is shown that the creation of a system for the near-field detection of PHOs coming from the daytime sky requires the use of a space-based system. A concept of such a system has been developed in which one or more optical telescopes are placed in the vicinity of the L1 libration point for the Sun-Earth system (Shugarov et al. 2021).

3 Meteoroids and safety of space activity

A variety of small bodies either reside in near-Earth space, or approach the Earth, sometimes coming from the farthest regions of the Solar system. The smallest bodies constantly collide with the Earth, larger ones hit our planet less often, but, as a rule, arouse great interest among people. Figure 4 shows summary statistics of the total number of collisions of natural objects with the Earth (per year).

The original figure (from Drolshagen et al. 2017) is supplemented with gray shading to identify meteoroids, indicators of methods for observing particles of different mass ranges, and a straight line that qualitatively corresponds to the universal law of the mass spectrum of different objects in the Universe. A discussion of this universal mass spectrum can be found in Shustov (2019).

Unlike relatively large bodies (asteroids and comets), meteoroids and dust particles in near space are studied by the manifestations of their interaction with the Earth's atmosphere using meteor astronomy methods or with the help of collision sensors on board spacecraft. The meteoroid risk in near-Earth space is basically caused by 1–10 mm meteoroid bodies (Murtazov 2018). Collisions with larger projectiles can cause more serious damage, but their number is relatively small. According to the model of Cour-Palais (1969), the flux of meteoroids with a mass greater than m can be estimated by the formula $\log N = -14.37 - 1.213 \log m$, where N is measured

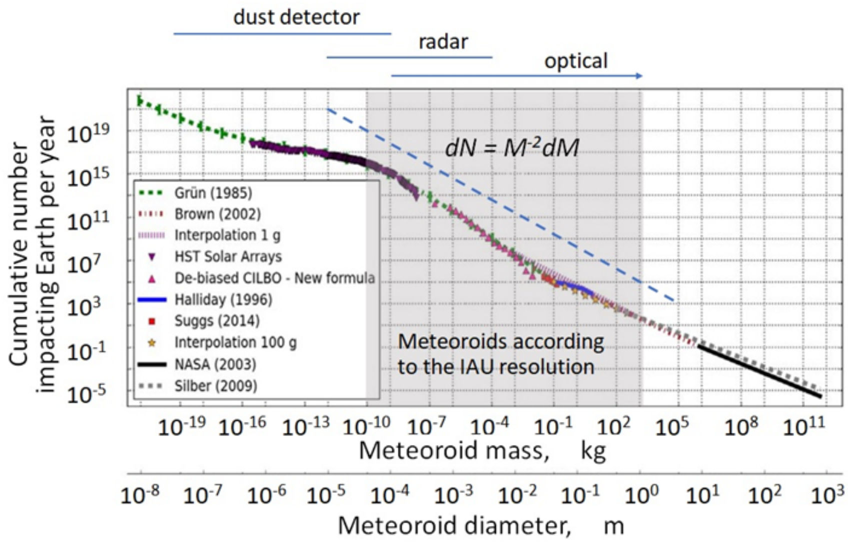

Fig. 4. Frequency of collisions with the Earth.

in $1/(\mathrm{m}^2\,\mathrm{s})$, and m in grams. For $m = 10^{-6}$ g the flux is $\sim 2.5\,\mathrm{m}^{-2}\mathrm{yr}^{-1}$, for $m = 1$ g the flux is almost negigible $\sim 1.4 \times 10^{-7}\,\mathrm{m}^{-2}\mathrm{yr}^{-1}$.

There are three main families of models (software) of the meteoroid environment.

In Russia, since 1987, we have been using the national standard GOST 25645.128-85, which establishes a model for the spatial distribution of meteor bodies with a mass of $10^{-6} - 10^{2}$ g in the ecliptic plane up to distances of $\sim 10^{6}$ km and bodies with a mass of $10^{-9} - 10^{-6}$ g within 200–1000 km from the Earth. In relation to space debris, since 2022, we have been using the national standard GOST R 25645.167-2022 “Space environment (natural and artificial). A model of the spatiotemporal distribution of the density of flows of technogenic matter in near-Earth space”.

The ESA MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model is designed in such a way as to give a realistic description of the natural environment and the environment consisting of solid particles created by man. Meteoroid environment is described by Grün interplanetary flux model (Grün et al. 1985), which assumes an isotropic distribution of meteoroids based on lunar crater data, zodiacal light, and in situ measurements. The latest version, MASTER–8, is described in Braun et al. (2021).

The NASA Orbital Debris Engineering Model (ORDEM) Series is designed to provide reliable estimates of the flux of orbital debris onto spacecraft and into the field of view of a telescope or radar (see, e.g., Flegel et al. 2010). The meteoroid situation is handled by NASA's Meteoroid Environment Office (MEO).[6] MEO is responsible for support of the Meteoroid Engineering Model (MEM). Some of the revolutionary aspects of MEM are a) identification of the sporadic radiants with real sources of meteoroids, such as comets, b) a physics-based approach that provides accurate fluxes and directionality for interplanetary spacecraft in the range from 0.2 AU to 2 AU, and c) velocity distributions obtained from theory and confirmed by observations. Given a state vector, the model outputs mass-limited or penetrating fluxes and average impact speeds and distributions on the surfaces of a cube-like structure with the ram face oriented along the spacecraft velocity. The current version of MEM, MEM 3 (see Moorhead 2019), generates environment data for spacecraft orbiting the Earth, Moon, Mercury, Venus, or Mars, or traveling through interplanetary space.

The models presented above relate to the situation in near-Earth space. It is clear that meteoroids and dust are our guests. Many researchers believe that comets are the sources of the dust (see, e.g., Yang and Ishiguro 2018). However in Busarev et al. (2016) and other papers by these authors it was shown that a number of asteroids exhibit so-called sublimation-dust activity and asteroids can lose solid matter in significant quantities. Shustov et al. (2022); Zolotarev and Shustov (2023) argued in favor of the fact that the rate of dust emission from asteroids activated by collisions can be comparable to a cometary source. It is important to deal with the issue of particle balance, because particles of asteroidal origin differ significantly in density (and in breakdown properties) from cometary particles. Also, to create a comprehensive dynamic model of the meteoroid environment in near-Earth space, improved models of the origin and dynamics of meteoroid streams are needed.

4 The need for cooperation

Both the NEO Problem and problem of safety of space activities in the near-Earth space are global in nature. This implies the need for international cooperation. On the other hand, effective participation in international cooperation requires a substantial national program.

The documents adopted by the UN note the leading role of three information and analytical centers on the NEO problem (two of them controlled by the United States):

- MPC (Minor Planet Center).[7] It works under the auspices of the IAU, is located in the USA and funded by NASA;

[6] https://www.nasa.gov/meteoroid-environment-office/—accessed: 24 July 2024.
[7] https://minorplanetcenter.net/—accessed: 24 July 2024.

- NASA NEO Program Office at JPL (NASA Program Center on the NEO problem in the Jet Propulsion Laboratory);[8]
- ESA NEO Coordination Centre.[9] The NEOCC is ESA's centre for computing asteroid and comet orbits and their probabilities of Earth impact.

There are no Russian centers in this elite list, but there is hope that after the implementation of the "Milky Way" project a Russian center with a world-famous name will appear here.

Two major project (programs) for international cooperation in the NEO field are supported by the UN. They are IAWN and SMPAG:

IAWN (International Asteroid Warning Network)[10]

The IAWN is a virtual network of institutions performing functions such as detecting, monitoring and physically characterizing the population of potentially hazardous near-Earth objects, as well as maintaining an internationally recognized coordination center for receiving, confirming and processing all near-Earth object observations. The current list of IAWN signatories (currently 52 names) include major space agencies, institutes (five instistutions from Russia among them), observatories and experienced amateurs (e.g., G. Borisov from Russia). INASAN has been involved in the network since 2016. As part of the international cooperation of IAWN, an observational experiment was conducted in 2017 to recover and follow-up the asteroid 2012 TC4. For four months, astronomers from the USA, Canada, Colombia, Germany, Israel, Italy, Japan, the Netherlands, Russia, and South Africa tracked the asteroid using ground-based and space telescopes in the optical and radio ranges in order to study its orbit, shape, rotation features and composition (see Reddy et al. 2019). The rich observational material obtained during the campaign made it possible, in particular, to accurately calculate the orbit of the asteroid 2014 TC4. On the Russian side, observations of the asteroid 2012 TC4 were conducted by the Terskol observatory with the Zeiss-2000 telescope (see Fig. 5).

Space Mission Planning Advisory Group (SMPAG)[11]

This is a group of Member States that have space agencies. The primary objective of SMPAG is to prepare an international response to the NEO threat by sharing information, developing joint research options and mission capabilities, and conducting NEO mitigation planning activities. Roscosmos is a member of SMPAG, but is not yet active.

[8] https://cneos.jpl.nasa.gov/—accessed: 24 July 2024.
[9] https://neo.ssa.esa.int/—accessed: 24 July 2024.
[10] https://iawn.net/about/members.shtml—accessed: 24 July 2024.
[11] https://www.cosmos.esa.int/web/smpag—accessed: 24 July 2024.

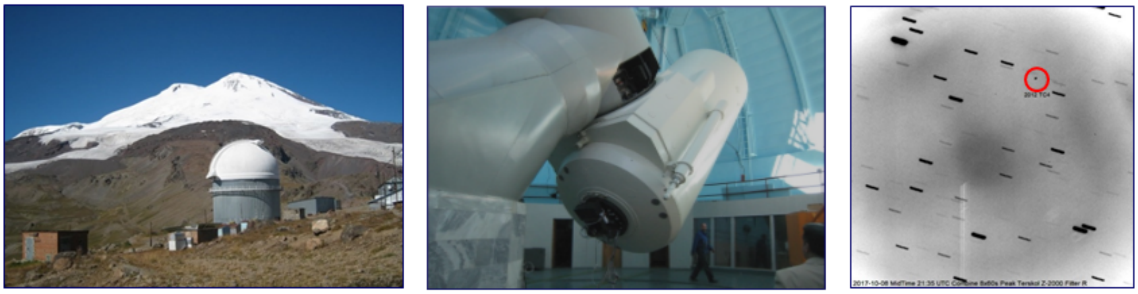

Fig. 5. Terskol observatory, Zeiss-2000 telescope, 2012 TC4 (in a red circle).

The Working Group on Astronomy of the BRICS countries (BAWG) initiated the project "BRICS Intelligent Telescope and Data Network (BITDN)"[12] (former name—"BRICS Optical Transient Network"). It is a dedicated flagship programme of the BRICS countries to develop a network of ground-based optical telescopes to survey the entire sky to detect short-duration optical transients and provide the capability to follow-up multi-wavelength and multi-channel transient objects (see Buckley et al. 2021). In terms of NEO topics, BITDN will meet the goal of successfully detecting and determining the orbit of NEOs down to tens of meters in size across the entire sky every few hours, reaching a limiting magnitude 20^{m}. The survey observation strategy will allow targeted tracking of PHO alerts, allowing the path of an approaching object to be tracked and the most likely impact location to be calculated.

In recent years Roscosmos is developing a new Russian system of telescopes and satellites called the Milky Way which is designed to ensure the safety of space activities in near-Earth space[13]. The Milky Way system will play an important role in monitoring and warning about dangerous situations in outer space near the Earth. It includes up to 65 telescopes, as well as a space segment represented by a group of satellites that will constantly monitor near-Earth space. The first of them is planned to be launched in 2027. The project will deal with several problems: space debris, spaceweather and NEO problem. The introduction of the Russian Milky Way will contribute to the development of scientific potential, more accurate forecasts and responses to potential threats in and from space.

[12] https://www.bricsastronomy.org/brics-intelligent-telescope-and-data-network/—accessed: 28 July 2024.

[13] https://tass.com/science/1792063?ysclid=lz5maokqlw391262954—accessed: 28 July 2024.

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