9th IAA Planetary Defense Conference – PDC 2025
5–9 May 2025, Stellenbosch, Cape Town, South Africa

IAA-PDC25-04-204

NEO and imminent impactor discoveries from Hungary: recent results and lessons learnt

Krisztián Sárneczky[a,*], László L. Kiss[a,*], Norton O. Szabó[a], Szabolcs Velkei[b]

[a] *Konkoly Observatory, HUN-REN Research Centre for Astronomy and Earth Sciences, H-1121 Budapest, Konkoly Th.M. 15-17, Hungary*
[b] *Machine Intelligence Inc, H-2015 Szigetmonostor, Horánygyöngye 102/b, Hungary*

Abstract

2022 EB5, 2023 CX1 and 2024 BX1: these are the three recent imminent impactor discoveries from the Piszkéstető Mountain Station of the Konkoly Observatory. They make up about one percent of all NEO discoveries from our observatory and here we provide a detailed description of our approach and methodology that led to this noticeable sensitivity to these little impactors. After outlining the historical background of astronomical discoveries from Hungary, we introduce our recently upgraded survey instrumentation and outline the observational strategy and its implementation. We highlight the importance of strong feedback between analysis and ongoing data collection, maximizing the value of immediate follow-up. Finally, we discuss plans for moving forward to increase the sensitivity and the temporal coverage of our survey.

Keywords: Near-Earth Objects, imminent impactors, NEO survey, Piszkéstető

1. Introduction

Astronomical discoveries from Hungary – such as the discovery of new asteroids, comets, supernovae, and other transient objects – have always been intimately connected with the continuous development of the Konkoly Observatory in Budapest, founded as state-funded astronomical institute in May 1899. Systematic monitoring of the transient and moving sky began in the 1930s, when György Kulin (1905-1989), a very enthusiastic observer with the 24″ telescope located in the Budapest headquarter of the institute discovered 21 main-belt asteroids and one comet between 1936 and 1942. After World War II, Kulin was forced out of professional astronomy and then he switched to science popularization (with great successes to be told elsewhere).

The second wave of discoveries came with the opening of the Piszkéstető Mountain Station of the Konkoly Observatory in the Mátra mountains, approximately 80 kms north-east of the capital. Here the first telescope to begin scientific operations in 1962 was a 60/90/180 cm Schmidt telescope from Carl Zeiss Jena, which allowed capturing a 5-degree circular field-of-view (FoV) on 16×16-cm glass photographic plates. A systematic search for extragalactic supernovae started immediately and the most active observer was Miklós Lovas (1931-2019). While his primary interest lay in supernovae, and hence the inventory of his discoveries is dominated by 42 of them found between 1963 and 1995, Lovas is also well-known for his five comets and one NEO. The latter is 1982 BB =(3103) Eger, a high-albedo minor planet suspected to be one of the sources of the aubrite meteorites [1].

It is a recently uncovered and hence less known fact that Lovas had a rare missed opportunity on 15 December 1974, when he recorded a strange streak near the Andromeda nebula (Fig. 1). After the full digitization of approximately 13,000 Schmidt plates taken between 1962 and 1997 was carried out,

*Krisztián Sárneczky, László L. Kiss
Email addresses: sarneczky.krisztian@csfk.org (Krisztián Sárneczky), kiss.laszlo@csfk.org (László L. Kiss), szabo.norton@csfk.org (Norton O. Szabó), szabolcs.velkei@mi.services (Szabolcs Velkei)

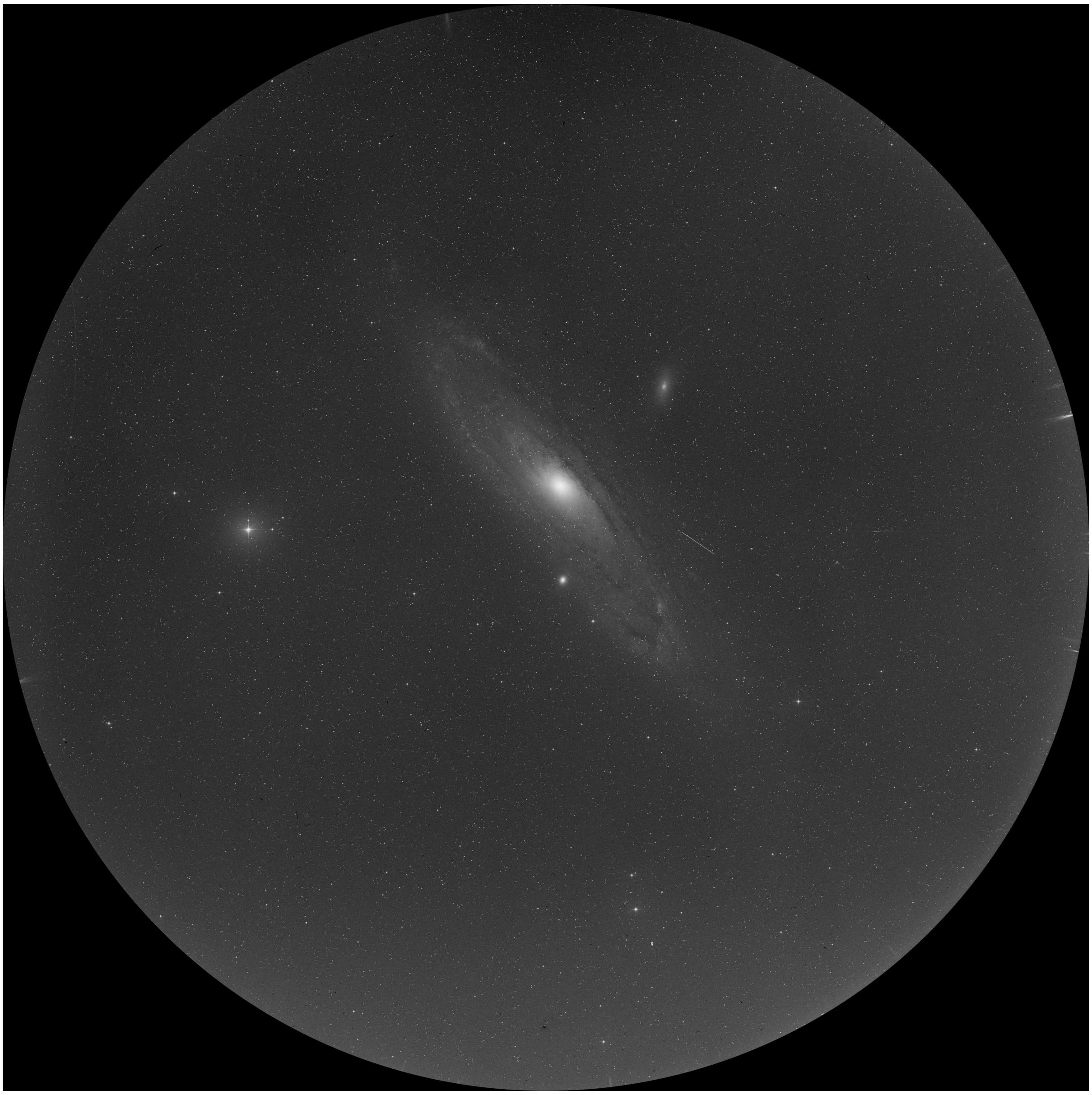

Figure 1: A pre-discovery image of (3200) Phaethon, the parent body of the Geminids meteor shower. Here we reproduce the full 5-degree circular field captured by Miklós Lovas on 15 December 1974, nine years before the official discovery using the IRAS satellite. Phaethon's trailed image is located slightly offset from the center to the right.

the first author KS in 2018 made the connection between the mysterious Lovas observation and the Apollo-type Near-Earth asteroid (3200) Phaethon, which was discovered in 1983 [2], nine years after the accidental detection by Lovas. Having been recorded on only two photographic plates and noted only days after the observations, Lovas had never had a chance to recover the fast-moving object. The two scanned fits files[1] were used to measure the coordinates of the previously unidentified moving object, which was thus identified with the parent body of the Geminids meteor shower [4].

With the advent of the CCD era, photographic observations quickly went out of fashion. At Piszkéstető, the first CCD in the Schmidt was installed in 1997 and in the following year KS and LLK started the initial continuous asteroid astrometry project, known as the JATE Asteroid Survey[2]. Since then the project has developed both in scope and instrumentation, which finally led to the current status of running a full-time dedicated NEO survey with the recently upgraded Schmidt-telescope.

[1] The full digitized Schmidt plate archive is available at `https://schmidt-heritage.konkoly.hu/` [3]

[2] `https://titan.physx.u-szeged.hu/~sky/jas/`

2. The CCD evolution at Piszkéstető

It is interesting to recall how the efficiency of discovering NEOs from Piszkéstető evolved with the continuous upgrades of the CCD in the focal plane of the Schmidt-telescope. Between 1997 and 2010 the main imager was a Photometrics AT200 CCD camera (1536×1024 KAF 1600 MCII coated CCD chip), with which the projected sky area was 29′×18′, corresponding to an angular resolution of 1,1 ″/pixel. With this setup, the JAS program discovered several hundred main-belt asteroids and one NEO over a period of 14 years.

The first upgrade was done in 2010, when a 4k×4k CCD was installed, delivering a total FoV of 70′×70′. The asteroid survey continued with approximately one week per month observing time on the Schmidt. Between 2010 and 2019, these efforts led to the discovery of several thousand main-belt asteroids and seven NEOs in total. While the discovery statistics showed some improvement with the larger FoV, it was clear that the full advantage of the Schmidt optics must be used to maximize the discovery rate.

In 2020, the Schmidt went through the most extensive refurbishment and upgrade to date. Using a custom-built field flattener lens as the camera window, a new imager was installed. The camera is a back-illuminated STA 1600LN 10k×10k CCD that provides a full imaging area of 95mm×95mm. This translates to about 9 square degrees FoV, with the same ∼1 ″/pixel image scale as with the previous two CCDs. We use a broadband Pan-STARRS w filter with a near-IR cutoff, so that we use the whole optical range to find the faint moving targets. Since the instrument upgrade the Piszkéstető NEO survey has been using 100% of the Schmidt telescope time.

The regular observations are taken in remote access mode on all clear or partially clear nights, except around the full Moon ±3 days, when measurements are only made when the atmosphere is completely cloud-free, dry and calm. The decision on taking data is done by KS, based on the remotely available weather and atmospheric data collected by various sensors, such as all-sky cameras, weather stations, and raw images with the Schmidt. The observations are controlled by the `ccdsh` environment, an in-house developed front-end control system based on various utilities including the `fitsh` package [5]. We take 12 to 18 sidereal tracking images per pointing, with exposure times varying from 9 to 26 seconds, depending on the background brightness, transparency and seeing of the sky.

The images are then processed by the Tycho Tracker [6], using the synthetic tracking method. Four GPU cards are used for the computations, typically with the granularity of 67%.

The completed 12-18 images series is processed and NEO candidates are identified by the observer until the next series is completed. This way, we already know whether there are any new NEOs in the images up to 12 minutes after the last exposure in the series. To extend the discovery space, for the past year we have been testing a new, AI-based software tool called NEODetect to identify fast-moving, streaking small planets, which are missed completely by the traditional methods (for details see our companion paper Velkei et al., this volume). Regardless of the discovery method, the coordinates of the new NEOs are immediately reported to the MPC, and the search is interrupted to start taking follow-up images.

3. Survey Performance and Statistics

As of April 2025, the total number of our NEO discoveries reached 277, and it keeps increasing every week by one or two new NEOs. This is a tremendous change compared to the past. The first-light observations of the STA-1600 LN CCD were obtained in August 2020. The year after was spent on testing several approaches and observing strategies until we ended up with the one described in the previous section. To see the annual statistics and possible trends, we took the three full years of standard operations, that is from 2022 to 2024.

First we show the full footprint of the Piszkéstető NEO survey for the whole three years in Fig. 2. The 3×3 deg fields are color-coded by the total number of visits. The mid-northern latitude of Piszkéstető (+47.9 deg) explains the dominance of the northern sky in the footprint; the NEO search rarely goes south of the ecliptic plane and the most southern parts of the ecliptic are completely left out. The galactic plane is also avoided for most of the time, although one NEO was once discovered in the dark dust lanes in the middle of the Cygnus Milky Way, where the dust obscuration of stars makes the discovery of moving objects possible despite the low galactic latitude.

To quantify the observations: the total sky coverage between 2022 and 2024 was 17,290 square degrees (about 42% of the whole sky), with typical observation counts between 20 to 50 (one field is counted only once on a given night even if it was revisited on the same night). The annual changes reflect the weather pattern:

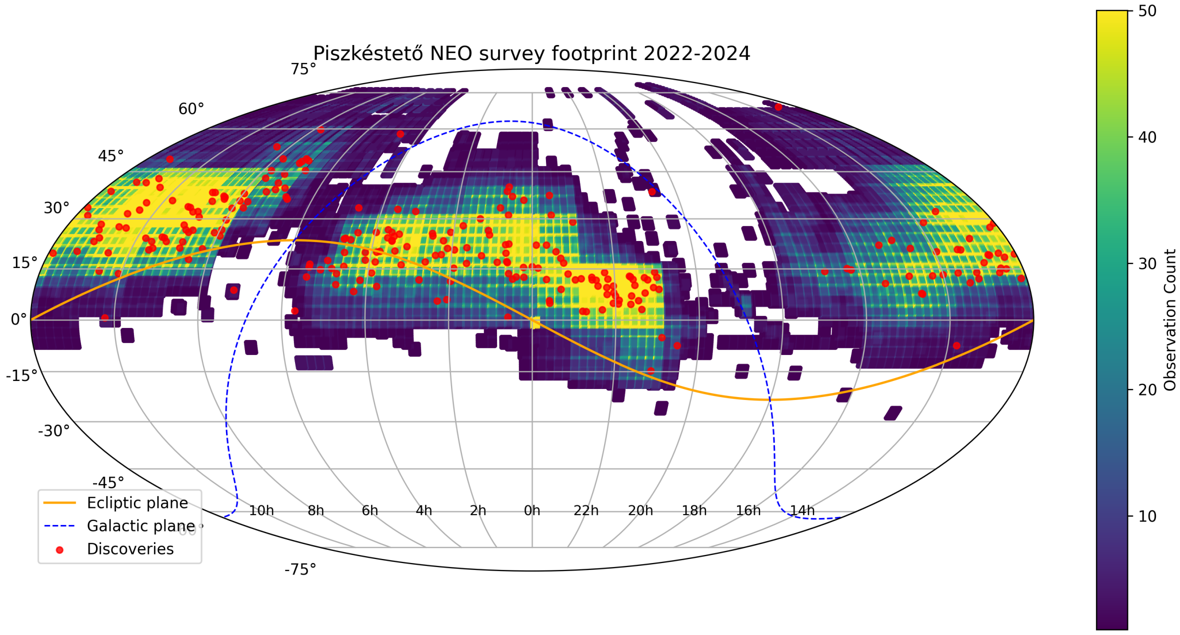

Figure 2: The Piszkéstető NEO survey footprint and the discoveries between 2022-2024.

- 2022: 11577 square degrees;
- 2023: 9480 square degrees;
- 2024: 8791 square degrees.

From these results, approximately 10,000 square degrees of sky coverage can be expected in a typical year, corresponding to about 25% of the entire sky.

The sensitivity of the Piszkéstető NEO survey can be characterized by two distributions. The first is the one that shows the apparent magnitude distribution of the NEO discoveries, plotted in Fig. 3. While there were a few discoveries in the bright range from 15 to 17 mag (usually during bright nights close to the full Moon), most of the new objects fall between magnitude 18-20, with a steep decline towards

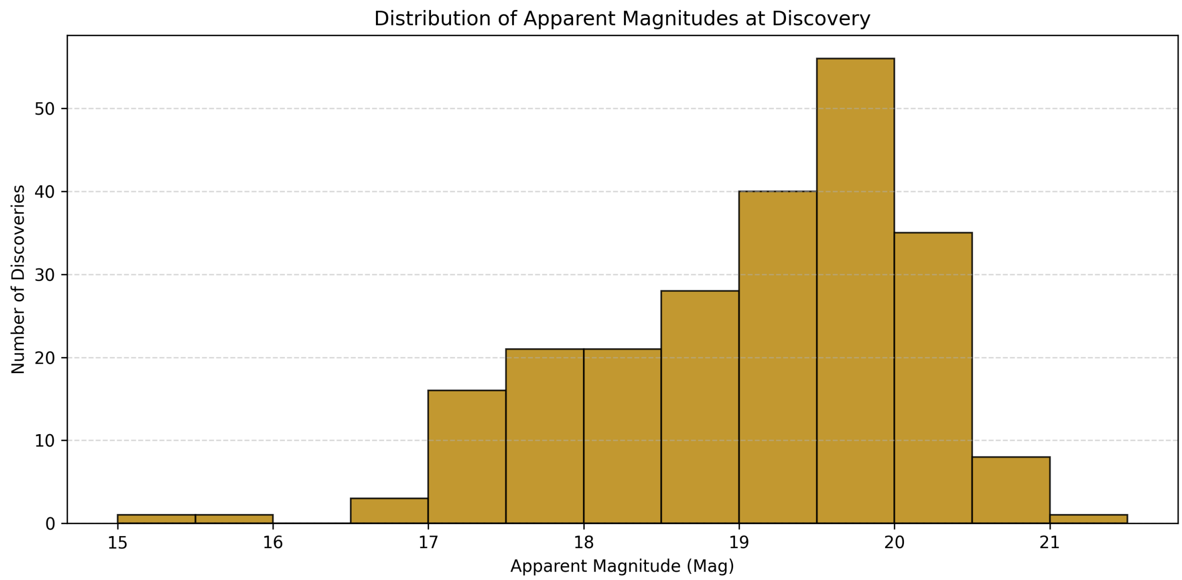

Figure 3: The apparent magnitude distrubution (tied to the Gaia G magnitudes) of the Piszkéstető NEOs between 2022 and 2024.

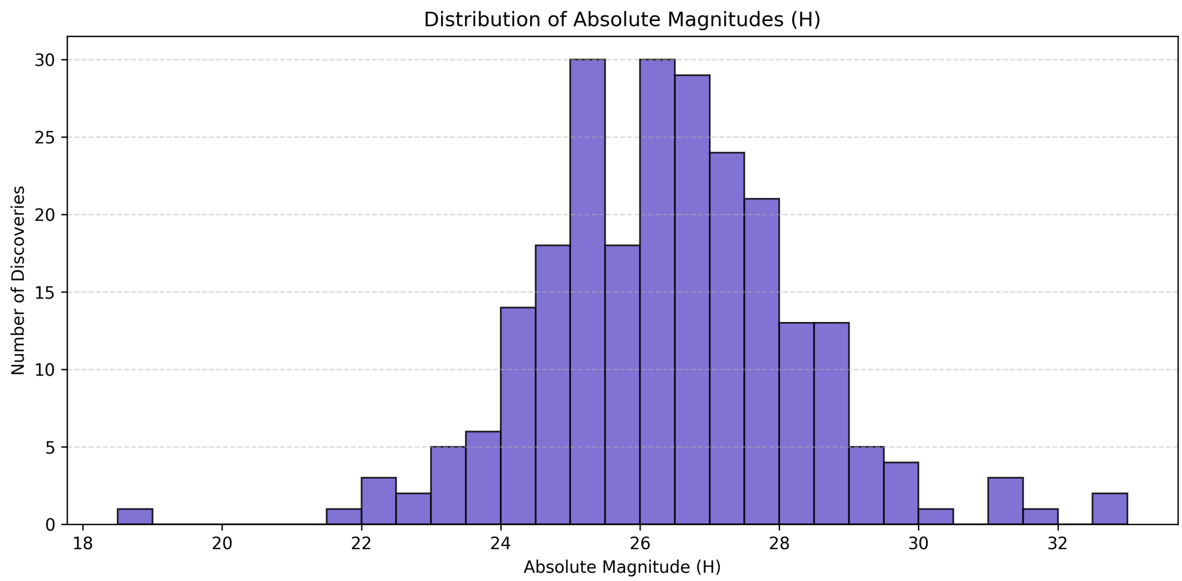

Figure 4: The absolute magnitude H distribution of the Piszkéstető NEOs between 2022 and 2024. The three imminent impactors all belong to the faint end of the histogram (H>30 mag).

the faint limit that is quite sharp at magnitude 21. (Note that our magnitude values are derived from field stars with Gaia G magnitudes, while the actual observations are done through a broad-band Pan-STARRS w filter with IR cutoff.) From the shape of the distribution one can conclude that our discoveries are close to being complete down to mag. 19-19.5, the maximum of the skewed distribution, while for the fainter targets we loose the sensitivity quite drastically.

A physically more meaningful distribution is that of the absolute magnitude H that can be converted into estimated diameters for various assumptions on the albedo. Our survey is the most sensitive for targets between H=24 and H=29, which corresponds to an estimated size-range of approximately 4 to 40 meters[3]. Our faintest discoveries (in absolute magnitude) are in the meter-sized range, which is already in the transition region between the smallest asteroids and the largest meteoroids.

In conclusion, our survey is mostly sensitive to possible Chelyabinsk-type impactors or ever smaller objects, thus providing a valuable service to the global efforts in planetary defense activities.

4. Highlights from Piszkéstető: three imminent impactors so far

The Piszkéstető NEO survey led to a surprising series of imminent impactor discoveries in the past three years. Between 2022 and 2024 we identified three objects – 2022 EB5, 2023 CX1, and 2024 BX1 – which were successfully tracked prior to atmospheric entry. Below, we summarize the discovery circumstances and follow-up observations for each case.

2022 EB5: During a routine survey on 11 March 2022, KS discovered the moderately bright object 2022 EB5 at 19:24 UTC, when it was approximately 109,000 km from Earth and about two hours prior to atmospheric entry. The asteroid had an apparent magnitude of 17.6–17.7 at discovery, and the finding was reported to the Minor Planet Center (MPC) approximately eight minutes later.

Follow-up observations were obtained between 19:51 and 19:54 UTC, by which time the asteroid's apparent motion had accelerated from an initial 52″/minute to 86–87″/minute, suggesting a likely impact trajectory. Astrometric measurements were submitted to the MPC after this second imaging series at 20:09 UTC. Continued tracking efforts allowed the asteroid to be observed until 11 minutes before impact, when it was only about 11,000 km from Earth's center.

The Center for Near-Earth Object Studies (CNEOS) at NASA later detected the visible radiation from the object's atmospheric entry over the Norwegian Sea, near coordinates 70.0° N, 9.1° W. Post-impact analysis suggests that 2022 EB5 was a C-type asteroid, with an estimated diameter of 5–6 meters, a comet-like density, and a very low albedo of less than 0.025 [7].

[3] `https://cneos.jpl.nasa.gov/tools/ast_size_est.html`

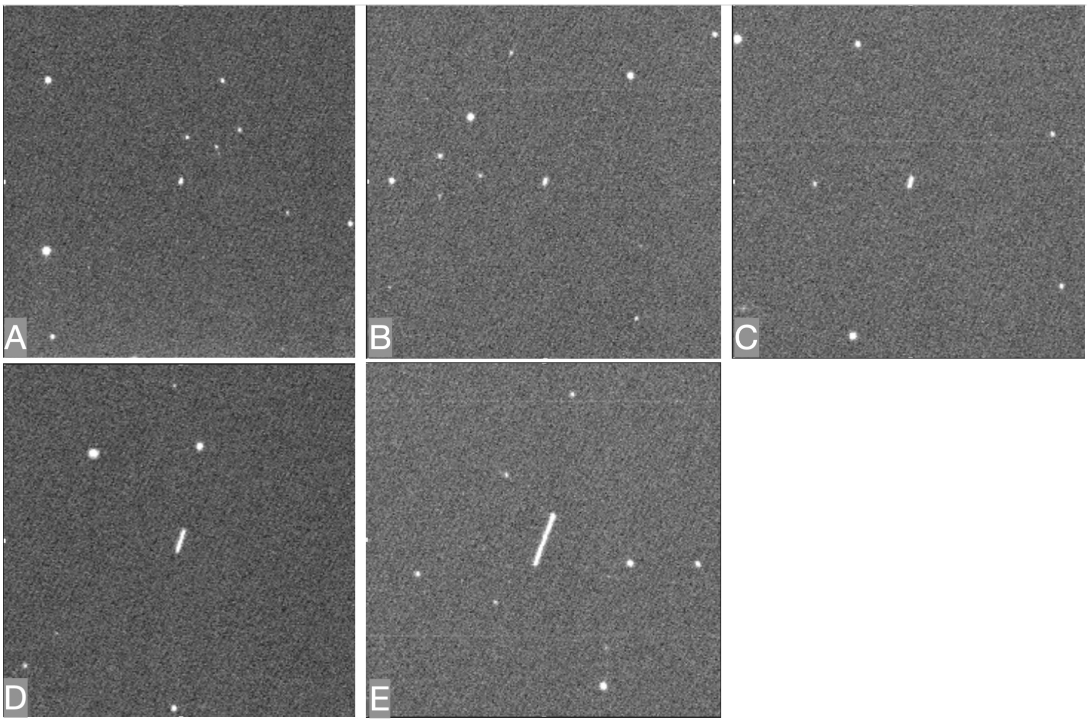

Figure 5: To highlight how the approaching asteroid was accelerating on the sky, here we show five 1 sec exposures of 2022 EB5 on 11 March 2022. A – 20:44 UT; B – 20:50 UT; C – 20:55 UT; D – 21:05 UT; E – 21:11 UT. The last one was taken only 11 minutes before the atmospheric entry.

2023 CX1: Less than a year later, KS discovered the asteroid 2023 CX1 on 12 February 2023 at 20:18:07 UTC. At the time of discovery, the object was already within the orbit of the Moon, at a distance of only 0.61 lunar distances (approximately 233,000 km), and had an apparent magnitude of 19.4. It was moving rapidly across the northern sky with an angular rate of 14″/minute and an inbound radial velocity of 9 km/s.

Recognizing its near-Earth nature immediately, KS assigned the temporary designation Sar2667 and reported it to the MPC's Near-Earth Object Confirmation Page (NEOCP) at 20:49 UTC, requesting urgent follow-up observations. A second observation half an hour later revealed that the asteroid was on a collision course with Earth. Subsequent observations by the Višnjan Observatory in Croatia, beginning at 21:03 UTC, confirmed the imminent impact.

The European Space Agency promptly publicized the event via social media, and observatories worldwide contributed to additional observations, significantly refining the predicted impact trajectory. 2023 CX1 reached a peak brightness of magnitude 13 shortly before entering Earth's shadow around 02:50 UTC on 13 February. It then faded rapidly and became unobservable until the impact. The final observation was recorded by Jost Jahn at the SATINO Remote Observatory in Haute Provence, France, at 02:52:07 UTC—only seven minutes before impact—when the asteroid was approximately 11,100 km from Earth's center (equivalent to about 4,700 km above Earth's surface).

The MPC assigned the official provisional designation 2023 CX1 at 04:13 UTC, approximately one hour post-impact. In total, at least 20 observatories submitted over 300 astrometric measurements before impact.

2023 CX1 was the seventh asteroid discovered prior to its impact with Earth, and notably, the third from which meteorite fragments were successfully recovered. It marked KS's second discovery of an impacting asteroid, following 2022 EB5.

2024 BX1: Continuing the sequence of pre-impact discoveries, the very small asteroid 2024 BX1, estimated to be only 40–50 cm in diameter, was detected on 20 January 2024 at 21:48 UTC [8], less than three hours before atmospheric entry. The discovery was made in a series of twelve 11-second exposures, during which the asteroid exhibited an apparent magnitude of 18.0 and a proper motion of 16″/minute. At the time of detection, it was located approximately 112,000 km from Earth.

Coordinates were reported to the MPC about 10 minutes after the initial observations, and follow-up imaging began 19 minutes later. Within the next 27 minutes, three follow-up observations were posted to the NEOCP. Both NASA and ESA warning systems quickly identified the object as a possible impactor.

A second series of observations commenced at 22:30 UTC, by which time the asteroid had brightened by 0.5 magnitudes compared to the time of discovery. Approximately 70 minutes after the initial detection, warning systems reported a 100% probability of impact, predicting atmospheric entry over Germany, approximately 60 km west of Berlin, at 00:33 UTC on 21 January 2024.

The final observation of 2024 BX1 was obtained at 00:24:44 UTC, just eight minutes before impact, when the object was only about 6,500 km from Earth's surface.

The recovered meteorites from 2024 BX1, officially named Ribbeck, were classified as aubrites [9]. As discussed in the Introduction, aubrites are linked to enstatite-rich (E-type) asteroids, and it is notable that one of their proposed parent bodies, the Near-Earth Asteroid (3103) Eger [1], was discovered by Miklós Lovas using the same 0.6-meter Schmidt-telescope at Piszkéstető that KS later used to discover 2024 BX1.

In all these discoveries — apart from luck — we think the most critical factor was real-time data processing. As soon as a NEO candidate is found (within minutes of the initial exposures), we stop the survey and switch to follow-up observations until we secure enough precision for impact probability determination and for orbit predictions for other follow-up observers. At this stage this is done by human interaction and is driven by the fact that there is a single dedicated telescope for NEOs at the Piszkéstető station.

5. Conclusions and further outlook

With the recent CCD upgrade, we have reached the limits of traditional techniques. That is why we are now entering a new phase that aims at real-time discovery of NEOs via accelerated image analysis with AI methods. These efforts and a new web-based service we developed for other NEO surveys are described in a companion paper by Velkei et al. (this volume).

Given the current approach, namely that when a NEO candidate is identified during the night, the Schmidt-telescope immediately switches from search to follow-up mode, it is clear that there is an increasingly important need for at least a second, fully dedicated telescope on-site that is capable both of searching and doing the follow-up for fresh targets. We are currently in the process of seeking funding for this second instrument, which we envision to essentially double the discovery rate from our Piszkéstető station. With NEOs we have the advantage that no comparable survey exists at our geographic longitude, a strength that we would like to utilize as long as we can.

Acknowledgments

The NEO survey at the Piszkéstető Mountain Station has been supported by a great variety of projects over the years. The latest instrument upgrade was funded by the GINOP-2.3.2-15-2016-00003 grant of the Hungarian National Research, Development and Innovation Office (NKFIH). The current activities are supported by the NEODetect project of the European Space Agency (ESA Contract No. 4000144612/24/D/BL). We are grateful to András Pál for the development and the maintenance of the `ccdsh` telescope control system, and to Zoltán Kuli and his team of the technical staff, who did a fantastic job in upgrading the Schmidt and its imager in 2020. Under the guidence of KS a number of colleagues took part in the observations and we thank for the kind help and assistance from Zsófia Bora, Borbála Cseh, Ágoston Horti-Dávid, András Joó, Csilla Kalup, Bálint Seli, Ádám Sódor, and Róbert Szakáts.

References

[1] M. J. Gaffey, K. L. Reed, M. S. Kelley, Relationship of E-type Apollo asteroid 3103 (1982 BB) to the enstatite achondrite meteorites and the Hungaria asteroids, Icarus 100 (1992) 95–109.
[2] S. Green, C. Kowal, 1983 TB, IAUC 3878 (1983) 1.
[3] S. Velkei, et al., Piszkéstető Schmidt Plate Archive, https://schmidt-heritage.konkoly.hu/ (2023).
[4] F. L. Whipple, 1983 TB and the Geminid Meteors, IAUC 3881 (1983) 1.
[5] A. Pál, FITSH- a software package for image processing, MNRAS 421 (2012) 1825–1837.
[6] D. Parrott, Tycho Tracker: A New Tool to Facilitate the Discovery and Recovery of Asteroids Using Synthetic Tracking and Modern GPU Hardware (Abstract), JAAVSO 48 (2020) 262.
[7] S. Geng, B. Zhou, M. Li, Near-Earth object 2022 EB5: From atmospheric entry to physical properties and orbit, A&A 670 (2023) A27.
[8] K. Sárneczky, T. Felber, B. Stecklum, L. Buzzi, G. Galli, F. Losse, M. Campestrin, M. Micheli, R. Bacci, P. Bacci, A. Sonka, P. Dupouy, J. Bernede, G. Galli, K. Korlevic, A. Valvasori, 2024 BX1, Minor Planet Electronic Circulars 2024-B76 (2024).
[9] P. Spurný, J. Borovička, L. Shrbený, M. Hankey, R. Neubert, Atmospheric entry and fragmentation of the small asteroid 2024 BX1: Bolide trajectory, orbit, dynamics, light curve, and spectrum, A&A 686 (2024) A67.