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EURONEAR: Data mining of asteroids and Near Earth Asteroids

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Besides new observations, mining old photographic plates and CCD image archives represents an opportunity to recover and secure newly discovered asteroids, also to improve the orbits of Near Earth Asteroids (NEAs), Potentially Hazardous Asteroids (PHAs) and Virtual Impactors (VIs). These are the main research aims of the EURONEAR network. As stated by the IAU, the vast collection of image archives stored worldwide is still insufficiently explored, and could be mined for known NEAs and other asteroids appearing occasionally in their fields. This data mining could be eased using a server to search and classify findings based on the asteroid class and the discovery date as "precoveries" or "recoveries". We built PRECOVERY, a public facility which uses the Virtual Observatory SkyBoT webservice of IMCCE to search for all known Solar System objects in a given observation. To datamine an entire archive, PRECOVERY requires the observing log in a standard format and outputs a database listing the sorted encounters of NEAs, PHAs, numbered and un-numbered asteroids classified as precoveries or recoveries based on the daily updated IAU MPC database. As a first application, we considered an archive including about 13 000 photographic plates exposed between 1930 and 2005 at the Astronomical Observatory in Bucharest, Romania. Firstly, we updated the database, homogenizing dates and pointings to a common format using the JD dating system and J2000 epoch. All the asteroids observed in planned mode were recovered, proving the accuracy of PRECOVERY. Despite the large field of the plates imaging mostly $2.27^\circ \times 2.27^\circ$ fields, no NEA or PHA could be encountered occasionally in the archive due to the small aperture of the 0.38 m refractor insufficiently to detect objects fainter than $V \sim 15$. PRECOVERY can be applied to other archives, being intended as a public facility offered to the community by the EURONEAR project. This is the first of a series of papers aimed to improve orbits of PHAs and NEAs using precovered data derived from archives of images to be data mined in collaboration with students and amateurs. In the next paper we will search the CFHT Legacy Survey, while data mining of other archives is planned for the near future.

1 Introduction

A *Near Earth Asteroid* (NEA) is defined as an asteroid having a perihelion distance (q) less than 1.3 AU. A *Potentially Hazardous Asteroid* (PHA) is a NEA having a Minimum Orbital Intersection Distance (MOID) less than 0.05 AU and the absolute magnitudes (H) less than 22 mag, which corresponds to objects larger than 150 m. This limit in size corresponds to asteroids large enough to potentially cause a global climate disaster and threaten the continuation of the human civilization (Chapman 1994). A *Virtual Impactor* (VI) represents a NEA (mostly recently discovered) whose virtual orbit associated with the present observing uncertainty could collide with the Earth (Boattini et al. 2003).

There are about 350 plate archives existing in the observatories around the globe holding more than two million photographic plates in their libraries. Created within the IAU Commission 9 by the Working Group on Wide Field Imaging, the Wide-Field Plate Database (WFPDB, www.skyarchive.org) contains the descriptive information for the astronomical wide-field ($> 1^\circ$) photographic observations stored in about 30 % of the estimated one thousand archives worldwide (Tsvetkov 1991, 2005). This wealth of astronomical information, specifically the WFPDB database, represents a great opportunity able to provide valuable scientific information for various astronomical objects observed occasionally in the past.

In spite of this opportunity, as well as the exponentially increasing number of digital images acquired by large telescopes stored in archives at major observatories, very few projects have been devoted to data mining of asteroids. Probably the major obstacles for a wider use of the archives include: (1) the lack of easily pointings for different archives (observing logs available in a homogeneous format, such as the WFPDB

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format accepted in VIZIER since 1997 (http://webviz.u-strasbg.fr/viz-bin/VizieR?-source=VI/90); (2) the lack of the public tools (software and servers) to facilitate the data mining; and (3) the lack of digitized archives (much easier to access and search than traditional photographic plate archives).

The Anglo-Australian Near-Earth Asteroid Survey (AANEAS) was one of the pioneering projects to use data mining as a tool to improve the orbits of NEAs (Steel 1998). AANEAS used both the UKST 1.2 m Schmidt telescope to observe in survey mode, and its plate archive library to search for the newly objects which have appeared occasionally on the plates. Following the discovery of a new NEA and the determination of its orbit, a integration backward in time could be performed in order to compare its ephemerides against some existing unknown trails from the image archive. The possible identification of such an object is called a *precovery*, a term which is derived from "pre-recovery" – the act of recovering an object in the past (Steel 1998).

During the last decade Boattini et al. (2001) carried out in Italy the Arcetri NEO precovery program (ANEOPP). This project exploited mainly two archives in the search for new NEAs, namely the Arcetri plate library consisting in copies of the Palomar Observatory Sky Survey, the UKST southern sky survey, and the Digital Sky Survey. In only two years, the ANEOPP project was quite successful in precovering about 80 objects soon after their discovery, these becoming multi-opposition objects from single-opposition, with an orbit very much improved. A special focus was placed on NEAs in danger of being lost due to insufficient observations (e.g., the NEA 1998 NU), as well as on VIs in order to improve their orbits using precovered positions and remove their VI status (e.g. the PHA 2000 PN9).

The DLR-Archenhold Near Earth Objects Precovery Survey (DANEOPS; Hahn 2002) was initiated to systematically search existing photographic plate archives such as the Palomar Observatory Sky Survey (POSS, 1.2 m Oschin Schmidt telescope) and the Anglo-Australian Observatory (1.2 m UK-Schmidt telescope), i.e. using DSS 1 and 2 from the STScI Digitized Sky Survey. During about two years, this program precovered or recovered some 150 objects, mostly NEAs.

On December 20, 2004 the Minor Planet Center announced the discovery of the famous asteroid 2004 MN4, namely Apophis (Sansuario & Arratia 2008). This object was discovered actually six months earlier by Tucker, Thollen and Bernardi from Kitt Peak, according to the data collected in two nights which presented some timing and astrometric problems. Just when the Christmas holidays were about to begin, it was already apparent that Apophis will become a VI PHA in 2029. According to the NEODyS/CLOMON2 system, this object was flagged to have an impact risk of TS = 2 on the Torino Scale (Binzel 2000) which was raised later to an unprecedented TS = 4 and an infamous 1 in 38 chances of impact. This result was obtained based on more than 200 new observations gathered in 20 runs performed within one week following a call for new data which in fact aggravated the situation. Fortunately, the tense problem was solved using some precovery positions obtained by Gleason et al. (Gleason et al. 2004) based on some Spacewatch observations from March 2004 which extended the orbital arc to 9 months, ruling out any possible impact in 2029. Here is how only one precovered position could degrade a VI object to a PHA, ruling out a potential impact with the Earth, at least for a while.

Created in 2006 in Paris, the European Near Earth Asteroids Research (EURONEAR) is a project which envisions to establish a coordinated network available to observe, discover and study NEAs and PHAs using 1–2 m class telescopes, as well as data archives existent in photographic or digital means in various archives around the globe (Vaduvescu et al. 2008). Via EURONEAR, we aim to increase the European synergies in a common network to provide specific tools and methods of research to the community willing to contribute in order to fight the asteroid impact hazard. In this first paper of this series, we present the software devoted to data mining of asteroids and its first application to the plate archive observed at the Astronomical Observatory in Bucharest, Romania. The paper is organized as follows: in Sect. 2 we present the method of search and PRECOVERY software. In Sect. 3 we include four applications based on a few image archives. The first uses the plate archive acquired in Bucharest. In the Appendix we present the database associated to this archive, performing the data mining of known asteroids using PRECOVERY.

2 PRECOVERY server

Part of the EURONEAR project, we have envisioned to built a server aimed to data mine any astronomical archive for known NEAs and other asteroids. This facility will be available to the whole astronomical community willing to search image archives to which they have access. Within the future frame of the Virtual Observatory, basically all image archives could be linked in a common *Sky Mega-Archive* available for data mining using basic search capabilities such as PRECOVERY. Thanks to the easy access via Internet to the public archives and databases available nowadays, the interest in data mining for NEAs and other asteroids should be expected to grow soon. The work could involve not only professional astronomers, but also people working in the education, students, amateur astronomers and the public outreach.

Built at IMCCE Observatoire de Paris, the SkyBoT tool was conceived to help astronomers in the data mining of the Solar System, to prepare and analyse astronomical observations, and to provide ephemerides of Solar System bodies in the frame of the Virtual Observatory (Berthier et al. 2006). The service uses a huge database (cca 2 TB) containing pre-computed ephemeris for all solar system objects, which is updated on a weekly basis. Using the capabilities of Sky-

BoT, an entire archive containing images (plates or CCDs) could be mined for precoveries and recoveries of known asteroids. The search could be implemented as a server which uses an input holding the observing log of the entire archive in a specific format. This should consist in sets of observations (one line corresponding to one observation) to include the pointings given by the centres of the observed fields (RA, DEC) at epoch J2000, the instrument field of view (along the RA and DEC directions in degrees), the Julian Date JD (or calendar date and time UT), exposure time (in seconds), and the IAU observatory code. Another approach could be to use the homogeneous WFPDB format addopted by VIZIER.

To perform the search, we wrote PRECOVERY, a PHP software which queries an entire archive of observations using SkyBoT, finds candidate images to hold asteroids appearing occasionally in the observed fields, and writes the output in a few lists to include PHAs, NEAs, numbered (NUM) and unnumbered (UNNUM) asteroids, sorting the results based on the asteroids' discovery date in two classes: *precoveries* (PREC, asteroids observed before their discovery date), and *recoveries* (RECOV, asteroids observed after their discovery). Some filters such as the limiting magnitude (set according to the telescope and instrument used) and filter could be applied based on the output of PRECOVERY in order to optimize the search based on specific science interests. The PRECOVERY software has been written in PHP in order to be easily embedded in the EURONEAR website (IMCCE 2008) and to be used in a network. In Fig. 1 we include the flow chart of PRECOVERY, showing the dependencies with the SkyBoT server and MPC databases.

To sort the findings given by SkyBoT, PRECOVERY uses the asteroids databases maintained by the Minor Planet Centre (MPC), namely the following lists of minor planets accessible from their *Unusual Minor Planets* website (IAU 2008): (1) List of Atens, Apollos, and Amors (from which we concatenate the list of known NEAs); (2) List of Potentially Hazardous Asteroids, and (3) List of Discovery Circumstances: Numbered Minor Planets. This database is updated by PRECOVERY to its server on a daily basis, in order to provide the most accurate information regarding the newest official denominations and orbits.

The total running time of a search depends obviously on the length of the archive and the observed field of view. Currently, the server could not handle parallel querying of SkyBoT, this feature being possible to implement in a future version in order to decrease the execution time of large archives. In the current version of PRECOVERY, an average $2^\circ \times 2^\circ$ field takes about one minute for a complete search and selection. Given the repetitive queries to SkyBoT and the relatively long response time of this server which integrates orbits of hundreds or thousands of minor planets to distant epochs in time, it is expected to take up to a few hours or days for a complete search of an archive which includes hundreds or thousands of observations. To optimize datamining of large archives, we recommend splitting the archive in more batches containing each up to 250 entries (observations).

The output of PRECOVERY consists in 7 files to be downloaded by the user following the end of the run, which are stored for retrieval on the EURONEAR server temporarily. Besides the plate number, PRECOVERY output simply appends the output of SkyBoT, each line representing one occurrence (precovery or recovery event). Besides the asteroid number and name or its temporary designation, the table lists the asteroid type, ephemerides (RA and DEC at J2000), computed V magnitude, the current ephemeris uncertainty for the requested epoch (CUE, in arcsec), and the apparent distance of the object from the plate centre (in arcsec).

3 Applications

3.1 Bucharest plate archive

The first archive available to us for this project started in 2005 was the photographic plate archive collected at the Astronomical Observatory in Bucharest since 1930 until present. This archive was acquired with the Prin Mertz double refractor (F = 6 m, D = 0.38 m) and holds about 13 000 plates imaging mostly Solar System objects (asteroids, comets, planetary satellites), thus an area subtending mostly the ecliptic, imaged during the past eight decades (Bocsa 2008). In the direct focus of the astrograph, the 24 cm × 24 cm plates subtend $2.27^\circ \times 2.27^\circ$, thus a large field possible to hold asteroids. To data mine this archive with PRECOVERY, we had to update first the database to a common format. In the Appendix we present the archive and its associated databases, applying them to PRECOVERY.

3.2 Other applications of Bucharest plate archive

Besides searches of minor planets, the Bucharest plate archive could be used for other studies, such as to improve the orbits of double star systems imaged occasionally in the archive. Using the Bucharest 2007 plate database in a separate study, we searched the double star systems appearing on plates based on the Washington Double Stars catalog (Curelaru 2007). Many of these double systems have insufficiently observed orbits, so archive work is welcomed to improve these based on old observations (e.g., acc. to the Journal of Double Star Observations). A preliminary search using the Bucharest plate archive found about 2300 plates from the Bucharest archive to include measurable double stars in about 3600 systems. We plan to continue this work in a dedicated paper.

3.3 Canada-France-Hawaii Legacy Survey

In a next paper we will apply PRECOVERY to search the Canada-France-Hawaii Legacy Survey (CFHTLS). This study has been conducted with positive results since 2007 (Vaduvescu & Curelaru 2007). Thanks to the large aperture of the 3.6 m CFHT telescope equipped with the large $1^\circ \times 1^\circ$

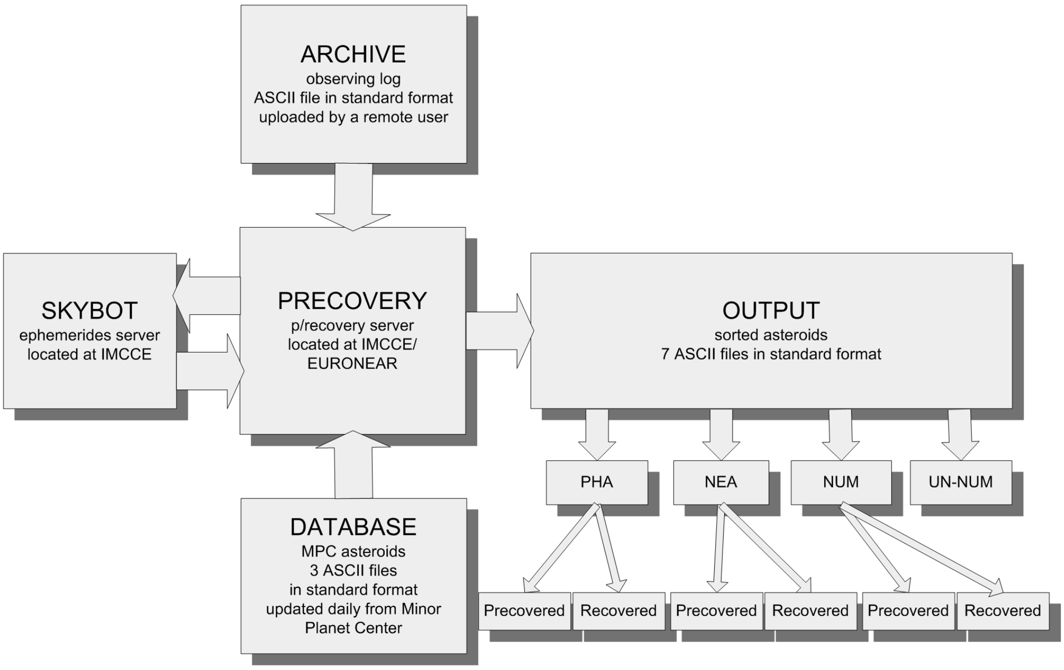

Fig. 1 The flow chart of PRECOVERY data mining software, showing the method and the main interactions with other servers and databases.

FOV of the MEGACAM camera, the PRECOVERY mining and image inspections have shown that about 250 NEAs and PHAs could be measured based on the CFHTLS archive, a work to be addressed in the second paper of this series.

3.4 Other image surveys

Aimed as a public facility to be used within the EURONEAR network, PRECOVERY could be employed for data mining virtually any other archive in the world (plates or images), provided that the user has the access first to the observing log holding the archive in a standard format. Besides the Bucharest plate archive and the CFHTLS image archive, we intend to apply PRECOVERY to mine other image archives acquired on large telescopes, in a distributed team effort to include also students and amateurs to work within the EURONEAR network. In a first instance, one requires only the observing logs corresponding to the archive in order to run the PRECOVERY search, then the access to only a few selected candidate images expected to hold the objects of interest.

At least four other archives have been identified for data mining of the most important NEAs, namely those in great need of data such as PHAs, VIs, and lost NEAs. First, we plan to extend our initial CFHTLS study to comprise the entire Megacam archive (FOV = $1^\circ \times 1^\circ$) acquired with the CFHT 3.6 m telescope and maintained online by the Canadian Astronomical Data Center (CADC). Second, we aim to mine the Wide Field Survey taken with the Wide Field Camera (WFC, $34' \times 34'$) of the 2.5 m Isaac Newton Telescope in La Palma, Canary. Third, we plan to use the Wide Field Imager archive ($34' \times 33'$) acquired the ESO/MPG 2.2 m telescope in la Silla, Chile and maintained online by ESO. Fourth, we plan to use the OGLE-III archive ($35' \times 35'$) acquired with the Warshaw 1.3 m telescope in Las Campanas, Chile. All these instruments have a small pixel size (around $0.3''$/pixel) and a very large field of view, being very adequate to ensure accurate astrometry for many NEAs in great need of data appearing occasionally in the field.

4 Conclusions

Besides new observations, mining the old photographic plates and CCD image archives represents one of the most important opportunity of research for improving the orbits of NEAs, and one of the aims of the EURONEAR project.

There are quite many old wide field plate archives around the globe, as counted by the WFPDB. This huge collection of astronomical information is still insufficiently explored, being possible to be data mined quite easily for known NEAs, PHAs, VIs, and other asteroids possible to appear occasionally in the observed fields. The resulted findings could be sorted as *precoveries* (observed before the discovery of a given object) or *recoveries* (observed after discovery). The resulting astrometry could bring important contributions in the direction of the NEA research and the PHA impact hazard.

In this sense, we created PRECOVERY as a public facility integrated within the EURONEAR project. PRECOVERY is a service which exploits the SkyBoT facility of IMCCE to search for all known Solar System objects for a given observation. Embedded within the EURONEAR website, PRECOVERY requires an observing log of a given archive to search, and the IAU observatory code. The output consists of seven ASCII files which list the occasional encounters of NEAs, PHAs, numbered and un-numbered asteroids, classifying them as precovery or recovery based on the daily updated IAU minor planet MPC databases.

In this paper we applied PRECOVERY to the plate archive taken at Bucharest Observatory using the 0.38 m Prin Mertz astrograph during the last eight decades, which used mostly 24 cm × 24 cm plates imaging a relatively large $2.3° \times 2.3°$ field of view. Because of the small telescope aperture, insufficiently to image objects fainter than $V \sim 15$, no PHA or NEA appearing occasionally on the plates were found in the archive. Nevertheless, all numbered asteroids and about 100 NEAs observed in the planned mode were precovered or recovered, proving the accuracy of PRECOVERY.

Other applications of PRECOVERY and the Bucharest plate archive could be used for similar searches. In a preliminary search using the same Bucharest plate database, we found about 2300 plates from the Bucharest archive to include about 3600 double star systems, possible to be used to improve the orbits of this systems. Another search using PRECOVERY applied to Canada-France-Hawaii Legacy Survey resulted in about 250 images to hold NEAs and PHAs measurable. Both these, as well as mining other archives for NEAs, will be address by our future work.

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A Bucharest plate archive

A.1 Overview of the archive

Celebrating its centenary in 2008, the Astronomical Observatory in Bucharest is affiliated today to the Astronomical Institute of the Romanian Academy (AIRA 2008). Despite the growing sky pollution due to its location in the capital Bucharest (2.5 million people), the observatory has contributed with many astrometric catalogs of stars, photographic observations of asteroids, comets, satellites, planets and stars observed during eight decades. The observatory has the IAU code 073.

One of the main telescopes of the observatory has been the Prin Mertz double refractor (F = 6 m, D = 0.38 m; WFPDB code BUC038). This equatorial astrograph was endowed with a small piggy-back Zeiss Canon photographic camera (F = 0.8 m, D = 0.16 m; WFPDB code BUC016) used for wider field imaging during the first two decades. From 1930 until 1951, photographic plates 13 cm × 18 cm were used in the focus of both refractors, providing a field of view of $1.70° \times 1.23°$ for the Prin Mertz refractor and $12.00° \times 8.67°$ for the Zeiss Canon camera. In 1952, a new numbering system was put in place to accommodate the observations using larger 24 cm × 24 cm plates which provided a field of view of $2.27° \times 2.27°$ in the focus of the Prin Mertz refractor. In total, during the last 78 years, about 13 000 plates have been acquired in all configurations using both refractors, from which about 12 800 plates have been taken using the Prin Mertz astrograph and only 180 plates using the Zeiss Canon camera.

In the past, the astrometric positions of the observed objects were measured manually with an ASCORECORD machine in the frame of stars from SAO or PPM catalogs.

Recently, about half of the entire plate archive were digitized at low resolution to be available for preview part of the WFPDB collaboration with the Working Group on Wide Field Imaging of the IAU (Bocsa 2008). A few plates were scanned and digitized recently at high resolution (2400 dpi) using a scanner UMAX Alpha Vista II, although no plan to scan the entire archive exists yet.

The Bucharest plate archive includes three related databases holding the observing logs of all observations performed at the observatory since 1930. The first database is updated monthly by the observatory in an ASCII format (Bocsa 2008), while the second included observations between 1930 and 1995 in a DBASE format (Vass 1994a). In 2007 we transformed the original ASCII database in a new database in MS Excel, which homogenizes the date and time in the standard JD format, transforming positions to a common J2000 epoch. We present next the three databases associated with the Bucharest archive.

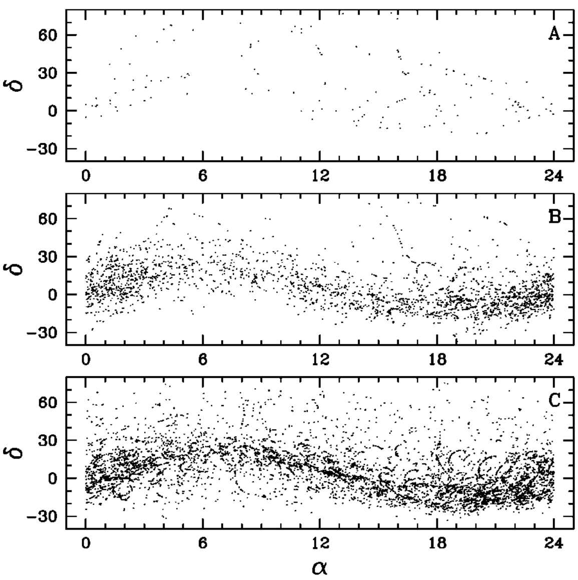

Fig. A1 Distribution of the centres of the Bucharest plate archive on the sky. *Panel A*: $12.00° \times 8.67°$ plates observed with the Zeiss Canon photographic camera (179 plates); *panel B*: $1.70° \times 1.23°$ plates observed with the Prin Mertz refractor (2708 plates); *panel C*: $2.27° \times 2.27°$ plates observed with the Prin Mertz refractor (7824 plates). The region of the ecliptic could be evidenced in all plots, being traced by most asteroids and comets observed between 1930 and 2005.

A.2 The original database (Bocsa 2008)

Every last photographic plate from the library was checked and counted in 1994, then entered in an ASCII database which includes the observing logs holding the following columns: the plate number, pointing of the telescope (RA, DEC), epoch (in a non-standard format, namely, B1900, B1930, B1950, J2000, etc), plate size (in cm), observing date and time (in a non-standard format, namely local sidereal time), number of exposures, exposure time, and the observed object. It would be difficult to work with this database, given its non-standard format to express the date/time and pointing of the fields, so we had to transform it first.

A.3 The 1994 database (Vass 1994a)

Vass (1994a) describes the wide-field plate archive database taken in Bucharest since 1930 until 1994, while Vass (1994b) makes a preliminary analysis of this database. Most observations focused on astrometry of minor planets (78 %), followed by fundamental stars (9 %), comets and nebulae (4 % each), and other objects (variable stars, radio sources, star clusters, double stars, major planets, etc). The exposure time were mostly less than 20 min (with less than 10 % plates exposed as long as about one hour), thus the limiting magnitude is expected to be quite reduced given the small 0.38 m refractor observing from a big city, namely $V \leq 15$ at its best. In fact, mostly due to the growing light pollution of Bucharest, the observations decreased during the last two decades, so the above figures regarding the surveyed objects did not change much.

A.4 The 2007 database (the present work)

Likewise the original ASCII database, the 1994 database created by G. Vass in DBASE conserves the original date and time recorded in local sidereal time, which is inconvenient for long time studies of the archive. Given this, we imported the original ASCII 2007 database in an MS Excel database, in order to facilitate a convenient access to the archive. First, we converted the observing dates and time to Julian Date (JD). Second, we transformed the original positions holding the telescope pointings expressed at different epochs to the common J2000 frame, correcting these by precession and nutation (Meeus 1999). Third, we included the field of view (FOV), taking into account the plate scale based on the instrument configuration (two refractors and two type of plates). Finally, we added the exposure times in case of multiple exposures of the same plate. Most of this work was done automatically in MS Excel in Windows and Gnumeric in Linux, doubled finally by some inspection and manual editing. A few entries (about 100) failing to specify the observing time were deleted. The final Gnumeric database was exported to two ASCII files which list 1906 observations before 1952 (the old series), and 8805 observations after 1952 (the new series), adding together 10 711 observations.

In Fig. A1 we plot the sky distribution of the Bucharest plate archive, according to the 2007 database. In the top panel A we include centres of the exposures using the 13 cm × 18 cm plates exposed in the focus of the Zeiss Canon photographic camera (179 plates). In panel B we include the exposures of the 13 cm × 18 cm plates in the focus of the Prin Mertz astrograph (2708 plates). Finally, in panel C we include the exposures of the 24 cm × 24 cm plates in the focus of the Prin Mertz astrograph (7824 plates) which constitutes 73 % of the entire database.

In the electronic Table A1 and Table A2 we include the 2007 database. The first table lists all observations before 1952 (the old series), and the second table includes all observations after 1952 (the new series). The new format includes the plate number, a flag listing the series, Julian Date (at start of exposure), the exposure time (in seconds), the plate centers at J2000 (RA in hours with decimals and DEC in degrees with decimals), the field of view (in the direction of RA and DEC, both in degrees), and the observed object (alpha-numeric). All fields are separated by the "|" character to ease the import of the fields.

A.5 Limiting magnitude

Due to the small aperture of the Prin Mertz refractor (D = 0.38 m), also to the growing sky pollution in Bucharest, the limiting magnitude is reduced to about $V < 15$ (Bocsa 2008). Actually, this limit has been reached only for a few hundred plates observed in the best conditions: the longest exposures, good weather conditions, low airmass, less light pollution, good developing process, and good archival conditions. For most of the plates in the archive, the limiting magnitude is estimated to only about $V < 12$ (Bocsa 2008).

To evaluate the limiting magnitude of the plates observed in the the best conditions, we inspected 8 plates scanned at 2400 dpi. The original TIFF images were transformed to FITS format for a smaller field ($46.2' \times 46.2'$) located at the centre of the plate, selected to maximize the image quality which is better near the centre. From the 8 plates, only one observed in 1965 (nr. 5089) was deep enough (exposure time 30 min) to produce a good quality FITS image. We inspected this image in IRAF using the DAOPHOT package (DAOFIND task to find all stars within 5σ detection limit, and PHOT to measure their magnitudes). We measured the instrumental magnitudes using 20 selected stars from the centre of the field whose apparent B magnitudes were taken from the USNO-A2 catalog (Monet et al. 1998). Their measured errors were around ± 0.2 mag, consistent with the catalog photometric errors.

In Fig. A2 we present the histogram (plotted as a solid line) showing the number of sources detected by DAOPHOT in the scanned image as a function of the apparent B magnitude. The shallow decrease of the curve could be related to about two reasons. The first relates with the detection of artifacts instead of real stars towards the faint limit, appearing most probably from the developing, archiving, and scanning processes. The second possible reason could be related with the comparison of magnitudes: while USNO-A2 catalog reports B magnitudes calculated from the original photographic magnitudes, no filter was used for the observations in Bucharest, therefore the brightness of sources detected on plates could be over evaluated. To check this effect further, we considered the USNO-A2 stars within the same exact image, whose scaled histogram was compared with the linear one of the plate in Fig. A2. There is a small apparent shift between the two histograms (around 0.5 mag) which appears to grow following $B \sim 13$, suggesting the two possible reasons. The plate histogram peaks around $B \sim 15$, although the limiting magnitude could reach $B \sim 15.5$, because we could identify stars as faint as this limit. Assuming an average colour of $0.5 < B - V < 1.0$ for most asteroids, it is prudent to consider the limiting magnitude $V = 15$ for the entire plate archives, but keep in mind that this is possible to reach only in the best conditions.

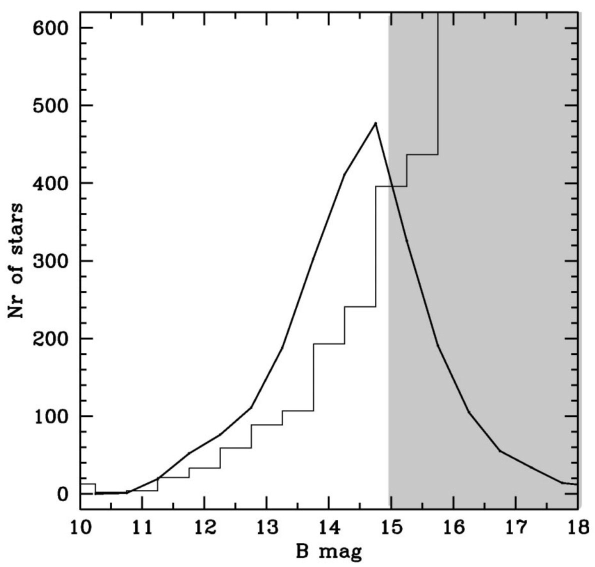

Fig. A2 The distribution of the observed B magnitudes of stars measured in the field of the plate nr. 5089 (exposure time 30 min). The peak of the histogram combined with the detection of stars having known USNO-A2 B magnitudes suggests a limiting magnitude $B \sim 15.5$. This corresponds to $V \sim 15$ at most, assuming $0.5 < B - V < 1$ for the entire asteroid population, reached only for plates observed, processed and stored in the best conditions.

A.6 PRECOVERY mining

We performed the data mining of the Bucharest plate archive for the new series database (1952–2005). We searched this archive only because SkyBoT currently does not accept epochs earlier than January 1, 1950. A future version of SkyBoT to be able to search epochs before 1950 requiring an update of the hardware (additional 2 TB) is expected to be implemented soon. A total of 8805 plates observed between January 1, 1952 and September 30, 2005 with FOVs mostly of $2.27° \times 2.27°$ acquired with the 0.38 m Prin Mertz refractor were considered for the search. The complete search took about one month and about 50 batches executed in separate runs (each holding about 200 plates on

Table A1 Sample of the Bucharest 2005 plate archive database including the old series of observations (1930–1951). The complete database is available in electronic form upon request.

Plate Nr. (old series)	JD (start exposure)	Exp. Time (s)	α Centre (J2000)	δ Centre (J2000)	FOV α (°)	FOV δ (°)	Object
1	2426113.44442028	2400	17.20714	37.0510	12.00	8.67	COMET 1930D
16	2426304.44093162	4200	5.28980	28.0757	1.70	1.23	(198) AMPELLA
44	2426449.41968583	900	13.98881	–7.7181	1.70	1.23	(236) HONORIA
75	2426488.36860231	720	16.99918	–15.9527	1.70	1.23	(8) FLORA
83	2426511.39929546	3660	18.36830	–9.9328	12.00	8.67	(107) CAMILLA

Table A2 Sample of the Bucharest 2005 plate archive database including the new series of observations (1952–2005). The complete database is available in electronic form upon request.

Plate Nr. (new series)	JD (start exposure)	Exp. Time (s)	α Centre (J2000)	δ Centre (J2000)	FOV α (°)	FOV δ (°)	Object
1	2434027.23065004	720	6.31462	0.9453	1.70	1.23	(41) DAPHNE
9	2434042.24232689	1080	7.73720	20.2960	1.70	1.23	(407) ARACHNE
1135	2435723.26344971	2340	18.50261	–10.1485	2.27	2.27	(3) JUNO
1139	2435723.48645027	2520	23.41830	–11.9084	2.27	2.27	(40) HARMONIA
1288	2435858.27297292	3000	3.33999	16.0132	2.27	2.27	(42) ISIS

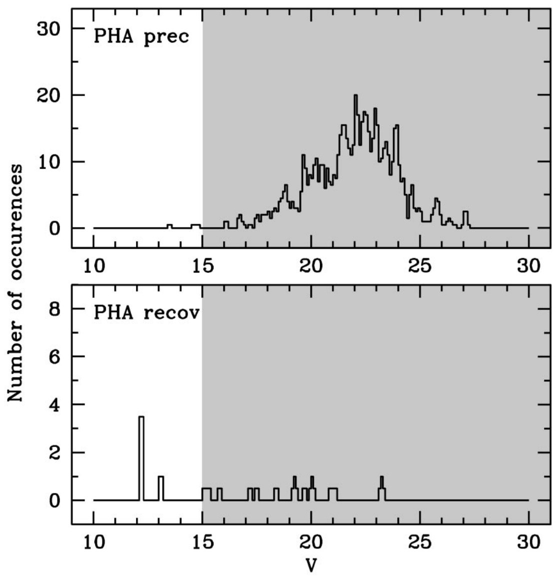

Fig. A3 The distribution of the findings of PHAs from the Bucharest plate archive. The region in gray was inaccessible to the refractor.

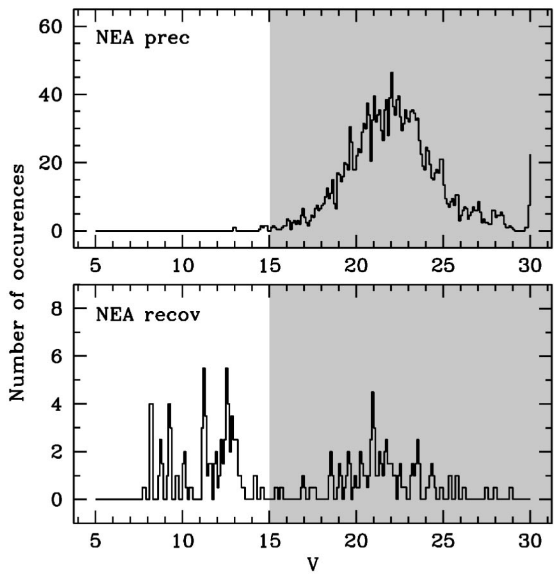

Fig. A4 The distribution of the findings of NEAs from the Bucharest plate archive. The region in gray was inaccessible to the refractor.

average). To perform the search, we used the MPC asteroid database published on February 6, 2008. Given the shallow limiting magnitude reached by the archive, most asteroids discovered after this date will be too faint to appear on the plates, so one could consider this search almost complete.

Table A3 shows a sample of the final list which includes the findings of the precovered PHAs searched in the 2007 Bucharest plate archive, listed without any filter regarding the limiting magnitude. The complete databases includes 7 ASCII files and is available in electronic form upon request. Table A4 lists the possible number of findings as a function of the asteroids' magnitude. In the first column we give the total number of findings found by PRECOVERY based solely on the asteroids' predicted positions by SkyBoT, with no filter of magnitude. Many PHAs, NEAs, NUMs and UNNUMs are located within the field of the plates in the archive, given the large field of view used.

Table A3 Sample of findings representing precovered PHAs in the Bucharest 2005 plate archive database. The complete database is available in electronic form upon request.

Plate Nr. (new series)	Aster. Nr.	Aster. Name	α (J2000)	δ (J2000)	Aster. Type (SkyBoT)	V (mag)	σ ($''$)	Dist. ($''$)
90	-	2002 FG7	15.510683424	–6.21185735	Amor I	21.8	0.100	2987.286
2610	-	2001 YV3	12.50622275	5.23994740	NEA	24.6	105.059	767.524
3985	11500	1989 UR	23.75836392	27.79120758	Amor I	18.8	31.407	3154.208
4592	89958	2002 LY45	15.48435510	–2.69252040	NEA	19.7	22.043	1879.372
6590	4660	Nereus	22.51019815	–6.51922595	Amor I	19.6	0.385	3790.449

Table A4 The number of findings of asteroids in the Bucharest plate archive 1952–2005.

Asteroid Class	Total Nr. Findings	Candidate $V \leq 15$ Findings
PHA prec	715	3
PHA recov	24	9
NEA prec	2 088	8
NEA recov	167	85
NUM prec	385 913	248
NUM recov	39 977	7 734
UNNUM (prec+rec)	349 753	3

In Figs. A3, A4, A5 and A6 we show the distribution of the PHAs, NEAs, numbered (NUM), and unnumbered (UNNUM) asteroids encountered by PRECOVERY to be located in some candidate fields, independently of the magnitude limit. The gray regions refer to invisible objects, according to the considered limiting magnitude $V = 15$. Although the astrograph was too small to image objects fainter than $V \sim 15$, all distributions show the potential of similar precovery searches using a similar FOV with larger telescope aperture.

As one could expect, the overwhelming majority of the findings list faint or very faint objects, inaccessible to the small 0.38 m refractor used in Bucharest. To select the candidate plates holding findings possible visible in the archive, we ordered the database taking into account the asteroids' predicted magnitude by SkyBoT. The second column of Table A4 lists the number of candidate plates holding possible findings of asteroids with magnitudes $V < 15$. In total, 105 encounters of NEAs and PHAs were found (both precoveries and recoveries). Checking these findings versus the original database, one could observe that the majority refer to objects observed in the planned mode. These objects were recovered by PRECOVERY in all cases, probing the validity of our search.

Considering $V = 15$ as the overall limiting magnitude of the archive (see Sect. A.5), we expect up to 3 PHAs possible to precover and 2 PHAs possible to recover observed in planned mode in 9 findings. Moreover, 6 NEAs are expected to be precovered in 8 findings and 7 NEAs to be recovered in 85 findings (most observed in planned mode, and only 3 objects occasionally). We include in Table A5 all possible findings (PHAs and NEAs up to the limiting magnitude $V = 15$). Following the inspection and scanning of these plates, we concluded that all the remaining 12 findings (NEAs and PHAs precovered or recovered occasionally) are actually invisible.

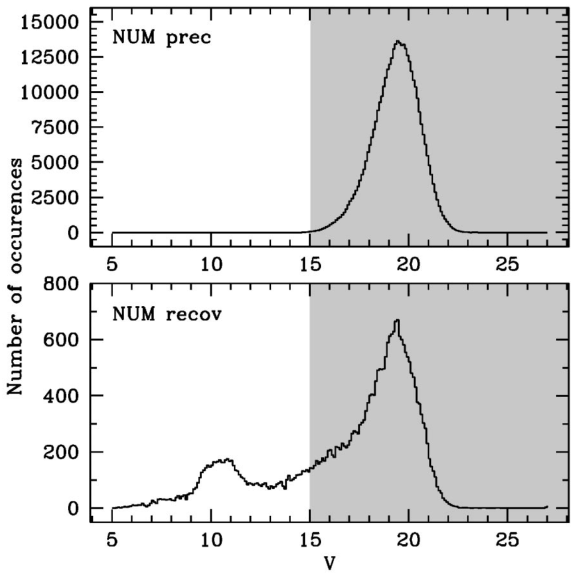

Fig. A5 The distribution of the findings of numbered asteroids from the Bucharest plate archive. The region in gray was inaccessible to the refractor.

Due to the shallow magnitude limit of the refractor, very few minor planets are actually visible in the archive, most being numbered asteroids. As one can see in Figs. A3 and A4, there are more encounters of precovered PHAs and NEAs than recoveries, which is normal given that the majority population of NEAs/PHAs has been discovered during the last two decades, compared with the archive which was mostly productive before the last period. One can observe two bulks in the NEAs recovered distribution, the first around $V \sim 11$ corresponding observed objects in the planned mode, and the other around $V \sim 22$, which coincides with the only peak in the NEA and PHA precovered distribution, corresponding to the limit of the present NEA surveys.

Table A5 NEAs and PHAs findings in the Bucharest plate archive 1952–2005 considering a limiting magnitude $V = 15$. Two types of findings were listed in Col. 3: "P" to denote planned observations, and "S" to denote occasional findings.

Asteroid Class	Asteroid Name	Type Find.	Plate Nr. (nr plates)	Date	Exp. Time (exp.×min)	Ast. Mag. V
PHA prec	2001 WN5	S	4371	Oct 1963	3×5	13.5
...	2004 HK33	S	4890	Jun 1965	15	14.6
...	1994 CN2	S	4428	Nov 1963	3×5	14.8
PHA recov	Geographos	P	(7p)	Sep 1969	various	12.2
...	Toutatis	P	(2p)	Jan 1993	8×8	13.1
NEA prec	1998 KU	S	7139	Oct 1971	14,10	13.9
...	Eric	S	8386	Oct 1973	2×6	13.9
...	Oze	S	10064	Dec 1985	15×10	14.5
...	2000 CN101	S	5873	Apr 1968	2×7	14.6
...	2000 CN101	S	5865	Apr 1968	2×7	14.6
...	1998 XB	S	5150	Nov 1965	3×4	14.8
...	Jason	S	6502	Oct 1970	3×4	14.8
...	Jason	S	6510	Oct 1970	3×4	14.8
NEA recov	Eros	P	(53p)	1972–75	various	7.8–13.3
...	Ganymed	P	(19p)	1972–73	various	11.2–12.9
...	Alinda	P	(9p)	1970–74	various	10.2–12.5
...	Tora	P	7717	Jul 1972	2×14	12.6
...	Boreas	S	460	Sep 1953	30,10	14.2
...	Seleucus	S	9541	Jun 1982	2×10	14.2
...	Ivar	S	5498	Apr 1967	2×5	14.6

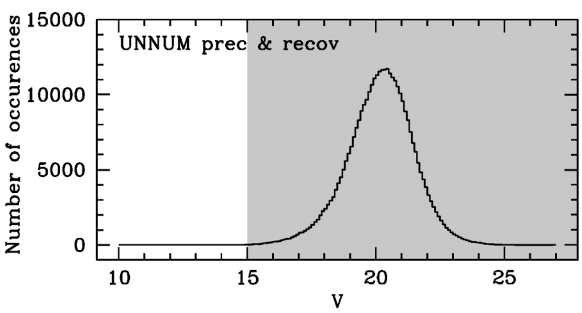

Fig. A6 The distribution of the findings of unnumbered asteroids from the Bucharest plate archive. The region in gray was inaccessible to the refractor.

As one can see in Fig. A5, the peak of the precoveries and recoveries of numbered asteroids is located around $V \sim 19.5$, while the peak of occasional observations of unnumbered asteroids is around $V \sim 20.5$ as can be observed in Fig. A6, both being accessible by 1 m-class telescopes. Two main bulges can be observed in Fig. A5, corresponding to recoveries of numbered asteroids, with the first between $5 \leq V \leq 13$ corresponding to minor planets observed in planned mode. A clear cut in the distribution of the magnitudes exists around $V = 13$, suggesting that this was the actual limiting magnitude possible using the given equipment.

