SsODNet: The Solar system Open Database Network

J. Berthier\textsuperscript{1}, B. Carry\textsuperscript{2}, M. Mahlke\textsuperscript{2}, and J. Normand\textsuperscript{1}

\textsuperscript{1} IMCCE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ Paris 06, Univ. Lille, France
e-mail: jerome.berthier@obspm.fr, jonathan.normand@obspm.fr
\textsuperscript{2} Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, France
e-mail: benoit.carry@oca.eu, max.mahlke@oca.eu

ABSTRACT

Context. The sample of Solar system objects has dramatically increased over the last decade. The amount of measured properties (e.g., diameter, taxonomy, rotation period, thermal inertia) has grown even faster. However, this wealth of information is spread over a myriad of articles, under many different designations per object.

Aims. We provide a solution to the identification of Solar system objects from any of their multiple names or designations. We also compile and rationalize their properties to provide an easy access to them. We aim to continuously update the database as new measurements become available.

Methods. We built a Web Service, SsODNet, that offers four access points, each corresponding to an identified necessity in the community: name resolution (quaero), compilation of a large corpus of properties (dataCloud), determination of the best estimate among compiled values (ssoCard), and statistical description of the population (ssoBFT).

Results. The SsODNet interfaces are fully operational and freely accessible to everyone. The name resolver quaero translates any of the ∼5.3 million designations of objects into their current official designation. The dataCloud compiles about 105 million parameters (osculating and proper elements, pair and family membership, diameter, albedo, mass, density, rotation period, spin coordinates, phase function parameters, colors, taxonomy, thermal inertia, and Yarkovsky drift) from over 3,000 articles (and growing). For each of the known asteroids and dwarf planets (∼1.2 million), a ssoCard providing a single best-estimate for each parameter is available. The SsODNet service provides these resources in a fraction of second upon query. Finally, the large ssoBFT table compiles all the best-estimates in a single table for population-wide studies.

Key words. Astronomical data bases – Catalogs – Minor planets, asteroids: general

1. Introduction

The decade of the 2000s has seen an order of magnitude increase in the number of known Solar system objects (SSOs), from roughly 50,000 to 600,000. While this number has doubled since, the revolution of last decade has been the even faster growth of measured properties of these bodies. About 2000 diameters and albedos had been determined from IRAS mid-infrared observations (Tedesco et al., 2002) and over 150,000 are available today (e.g., Mainzer et al., 2011; Masiero et al., 2011; Grav et al., 2011). Hundreds of detection of the Yarkovsky effect (Vokrouhlický et al., 2015) are available (e.g., Del Vigna et al., 2019; Greenberg et al., 2020), only 20 years after the first detection ever (Chesley et al., 2003)

This wealth of characterization (e.g., colors, albedos, rotation periods) has allowed multiple statistical studies on the forced orientation of family members by YORP effect (Slivan, 2002; Hanuš et al., 2016), the compositional distribution of the asteroid belt (DeMeo & Carry, 2014), the size-frequency distribution of asteroid families (Park et al., 2008; Masiero et al., 2013), the internal structure of minor bodies (Carry, 2012; Scheeres et al., 2015), and the origins of near-Earth asteroids (Perna et al., 2018; Devogèle et al., 2019; Binzel et al., 2019) among many others.

The benefit of all these developments has, however, not yet come to full fruition. If some catalogs are publicly available in machine-readable formats on the Planetary Data System\textsuperscript{1} (PDS), the Centre de Données astronomiques de Strasbourg\textsuperscript{2} (CDS), or alternative repositories (with unfortunately an endless variety of formats), a significant fraction of results are only tabulated within articles. Some journals offer machine-readable versions of these tables on their online versions, but only for recent articles. Furthermore, the designation of small bodies often evolves with time, from potentially several provisional designations, to a single number and finally an official name. Hence, the same object can be referred to by different labels in different studies, making its cross-identification over several sources a complex task. Accessing to all the characteristics of a given body, or a population, can thus be tedious, or even impractical.

Compiling estimates of SSO properties and deriving the best estimate for each is of high practical relevance for the computation of ephemerides in the Virtual Observatory
(VO) Web services we maintain (Miriade, SkyBoT, Berthier et al., 2006, 2008). Dynamical properties (i.e., osculating elements) are required to compute the position of SSOs, and physical properties are required to predict their apparent aspect as seen by an observer, such as:

- the apparent magnitude in V band, relying on the phase function (HG or HG₁G₂, Bowell et al., 1989; Muinonen et al., 2010);
- the apparent magnitude in any other band, requiring a color index derived from the spectral class (e.g., DeMeo & Carry, 2013; Popescu et al., 2018);
- the flux at mid-infrared wavelengths, computed from the diameter and albedo through a thermal model (Harris & Davies, 1999);
- the shape and orientation of a target on the plane of the sky (often referred to as physical ephemerides), based on its 3D shape model, rotation period, and spin-vector coordinates (e.g., Marciali et al., 2012).

Beyond ephemerides computation, an extensive and rationalized compilation of SSO properties has many applications, from detailed in-depth studies on specific targets to population-wide statistical description of parameters. Over the years, publicly available compilations of data have flourished, for instance the Jet Propulsion Laboratory Small Bodies Database³, the Las Cumbres Observatory NEOExchange⁴ (Lister et al., 2021), the Lowell observatory Minor Planet Services⁵ (Moskovitz et al., 2021), the NEOROCKS physical properties database⁶ (Zinzi et al., 2021), the Observatoire de la Côte d’Azur Minor Planet Physical Properties Catalog⁷ (MP3C, Delbo et al., 2018), the Size, Mass and Density of Asteroids (SIMD², Kretlow, 2020), and the SUPAERO ECOCEL®⁸ (Kovalenko et al., 2022). While these services fulfill many community needs, most do not provide a fast machine-machine interface.

We have thus designed a fully-scriptable Web Service named «Solar system Open Database Network» (SsODNet) which aims at providing the best estimate of a variety of parameters for every SSO. Owing to the complexity of compiling SSO data as depicted hereinabove, SsODNet consists in a suite of chained steps: from the identification of objects to the massive compilation of data, ending with the selection of best estimates, and summarizing them in a table. As each of these steps represents a typical task relevant for the SUPAERO ECOCEL®⁹ (Kovalenko et al., 2022), the Las Cumbres Observatory NEOExchange⁴ (Marciniak et al., 2012).

Beyond ephemerides computation, an extensive and rationalized compilation of SSO properties has many applications, from detailed in-depth studies on specific targets to population-wide statistical description of parameters. Over the years, publicly available compilations of data have flourished, for instance the Jet Propulsion Laboratory Small Bodies Database³, the Las Cumbres Observatory NEOExchange⁴ (Lister et al., 2021), the Lowell observatory Minor Planet Services⁵ (Moskovitz et al., 2021), the NEOROCKS physical properties database⁶ (Zinzi et al., 2021), the Observatoire de la Côte d’Azur Minor Planet Physical Properties Catalog⁷ (MP3C, Delbo et al., 2018), the Size, Mass and Density of Asteroids (SIMD², Kretlow, 2020), and the SUPAERO ECOCEL®⁸ (Kovalenko et al., 2022). While these services fulfill many community needs, most do not provide a fast machine-machine interface.

We have thus designed a fully-scriptable Web Service named «Solar system Open Database Network» (SsODNet) which aims at providing the best estimate of a variety of parameters for every SSO. Owing to the complexity of compiling SSO data as depicted hereinabove, SsODNet consists in a suite of chained steps: from the identification of objects to the massive compilation of data, ending with the selection of best estimates, and summarizing them in a table. As each of these steps represents a typical task relevant for the community, we propose a dedicated front-end (a Web service associated with an Application Programming Interface - API) for each, that we describe in the following sections:

- Section 2: quae ro builds a unique identifier for each object, associating all its aliases and providing the identity of the SSO,
- Section 3: dataCloud compiles the measurements and estimates of properties from many sources, providing the most-possible comprehensive data set of SSOs,
- Section 4: ssoCard provides the best estimate of each SSO property, and lists them in a single organized identifier card, and
- Section 5: ssoBFT summarizes the most-commonly requested of these parameters for all SSOs.

We then describe how to query these services (Section 6) before discussing the future developments of SsODNet (Section 7).

2. Name resolver: quae ro

The SsODNet.quae ro name-resolution service is built to address the issue of identification of SSOs, and more generally of all planetary and artificial objects gravitationally bound to a star. Upon the submission of any of the possible designations of a target, quae ro returns its official or main designation, together with all its aliases. To be compliant with the spirit of the VO ("Name resolver"), quae ro can also returns the equatorial coordinates of the object at a given epoch.

2.1. Context

The Solar system is populated by widely different types of celestial bodies: from planets and their satellites, to minor planets (comets, asteroids, Centaurs, Kuiper-belt objects) and their satellites, to artificial satellites, space probes, and space debris. Since the first exoplanet detection by Mayor & Queloz (1995), we know today about 5000 planetary objects that orbit around other stars than the Sun. Few rogue planets (e.g. OTS 44 or Cha 110913-773444) and two interstellar objects (1I/Oumuamua and 2I/Borisov) complete the picture of the planetary zoo.

The nomenclature of SSOs is entrusted to two groups under the auspices of the International Astronomical Union (IAU) Division F. The Working Group for Planetary System Nomenclature (WG-PSN) is in charge of naming features on planets, satellites, and asteroids. This group also names planets (although the IAU has never named a planet yet) and the natural satellites of major planets. The Working Group for Small Bodies Nomenclature (WG-SBN) is responsible for naming of all other small bodies (minor planets, satellites of minor planets, and comets). Both Working Groups share the responsibility for naming dwarf planets (IAU, 2020a).

As of today, there are no official name for exoplanets assigned by the IAU. The public names, assigned through a public naming process such as NameExoWorlds¹⁰ is distinguished from the official scientific designation, which follows the rules of the system used for designating multiple-star systems as adopted by the IAU (IAU, 2020b).

Spacecraft together with launchers, payloads, and space debris are indexed for safety and cooperation purposes. They are usually named by their funders (space agencies, laboratories, or companies). They are also assigned an International Designator (COSPAR ID), under the responsibility of the Committee on Space Research (COSPAR) of the International Council for Science (ICSU), and a Satellite Catalog Number (NORAD ID) attributed by the United States Space Command (USSPACECOM).

Since the designation of the major bodies of the Solar system (the Sun, the Moon, the eight planets), more than 1.2 million objects have been inventoried, classified, and named. As of today, there are more than 5.3 millions

³ https://ssd.jpl.nasa.gov/
⁴ https://neoexchange.lco.global/
⁵ https://asteroid.lowell.edu
⁶ https://neorocks.elecnor-deimos.com/web/guest/search-retrieval
⁷ https://mp3c.oca.eu
⁸ https://astro.kretlow.de/?SimDa
⁹ http://www.ecocel-database.com
¹⁰ https://www.iau-100.org/name-exoworlds
designations to name all of them. Objects can have multiple designations owing to the evolution of knowledge as well as changes in nomenclature over time\textsuperscript{11}. We illustrate this with the first asteroid discovered in 1801: Ceres. It is classified today as a dwarf planet. Its official designation is “(1) Ceres”: a number in parenthesis followed by a name. This official designation thus already contains two labels. But Ceres was also named by provisional designations over the years, assigned to past astrometric observations that had not been immediately connected to its orbit: “1801 AA”, “1899 OF”, and “1943 XB”. Ceres can thus be named in eight different ways. The all-time record is for comets P/Encke (1P) with 89 designations, and P/Encke (2P) with 89 designations. We present in Figure 1 the distribution of the number of designations by type of SSOs, and summarize it in Table 1.

Table 1: Statistics of the number of SSO designations by object class.

| Type               | Number of designations | min | max | mean | σ        |
|--------------------|------------------------|-----|-----|------|----------|
| Asteroids          | 2 42 4                | 2   |     |      |          |
| Comets             | 2 89 4                | 3   |     |      |          |
| Dwarf planets      | 6 10 6                | 2   |     |      |          |
| Planets            | 3 3 3                 | 0   |     |      |          |
| Satellites         | 2 6 2                 | 1   |     |      |          |
| Spacecrafts        | 3 10 3                | 1   |     |      |          |
| Spacejunks         | 3 4 3                 | 0   |     |      |          |
| Exoplanets         | 1 2 1                 | 0   |     |      |          |

\textsuperscript{11} \url{https://www.minorplanetcenter.net/iau/info/DesDoc.html}

\textsuperscript{12} \url{https://www.minorplanetcenter.net/iau/info/PackedDes.html}

\textsuperscript{13} \url{https://www.elastic.co/}

\textsuperscript{14} \url{https://lucene.apache.org/}

\textsuperscript{15} \url{https://doc.ssodnet.imcce.fr/quaero.html}

2.2. Quaero: \texttt{\textasciitilde k\textasciitilde aeg\textasciitilde ro/}

This is the core of \textit{SsODNet}. It ensures the reliability of the naming of SSOs, and allows to cross-match identifications between their actual names and the designations used over time in the various data sets. In August 2022, we count 1288838 solar and extra-solar objects for 5360208 designations (1:4 ratio).

\textit{SsODNet.quaero} is designed to fulfill four main functionalities:

- identify a SSO from its designation,
- explore the naming of SSOs using wildcard, regular expression, or fuzziness,
- resolve the name of a SSO into sky coordinates,
- provide an autocomplete feature that can be used to offer SSO name suggestions when a user types in an input field.

To achieve this goal, we gather, once a week, all planetary object designations from the Minor Planet Center (Marsden, 1980) for asteroids and dwarf planets, from the IMCCE’s CometPro Database (Rocher & Cavelier, 1996) for comets, from the Extrasolar Planets Encyclopedia (Exoplanet-Team, 2021) for exoplanets, and from CelesTrak (Kelso, 2021) for spacecrafts and debris. These designations are then stored and indexed in a dedicated database.

We use the NoSQL database Elasticsearch\textsuperscript{13} to manage the millions of designations. It is a full-text search engine based on the Apache Lucene library\textsuperscript{14}. Each object is defined by a set of fields (document) defining its Id, name, aliases, parent, type, etc. Documents are stored in an Elasticsearch index as JSON-format data. By default Elasticsearch tries to guess the correct mapping for fields, but to meet the challenges of planetary object identification, we specified our own mapping.

If SSO designations are indexed as individual strings, then a user can only find whole names. To allow the search of a name on a part of a designation, we decompose all SSO designations in small chunks (tokens). But, at this step, each token is still matched literally. This means, among other things, that a search for a name with or without an accent or a special character, or with mixed lowercase and uppercase characters, would possibly not match any name. To solve that, we define normalization rules to allow the matching of tokens that are not exactly the same as the search names, but similar enough to still be relevant.

For full technical information, we refer to the documentation\textsuperscript{15} of \textit{SsODNet.quaero} API.

3. Compilation of properties: \textit{dataCloud}

The \textit{SsODNet.dataCloud} service is designed to compile all published measurements and estimates of SSO properties. The \textit{dataCloud} uses \textit{SsODNet.quaero} to identify objects over their multiple designations. It also associates every estimate with a bibliographic reference and a method. Upon request, the \textit{dataCloud} returns all the estimates of a given property/parameter for the requested SSO.

3.1. Context

Starting with the planetary motion (Newton, 1760), the first studies of SSOs focused on their dynamics (Gauss, 1809), required to compute their ephemerides. From the distribution of their orbital elements, Hirayama (1918) discovered the dynamical families. Time-series photometry led to the determination of numerous rotation periods in the
first half of the twentieth century (e.g., Bailey & Pickering, 1913). The 1970s saw the advent of compositional and physical studies, with the first studies of diameter and albedo (e.g., Cruikshank & Morrison, 1973), mass and hence density (Schubart, 1974), and spectrophotometry and taxonomy (e.g., Chapman et al., 1975). The handful of SSOs with spin-vector coordinates and triaxial dimensions of the 1980s (Drummond & Cocke, 1989) became hundreds in the 2000s with the light-curve inversion technique (Kaasalainen & Torppa, 2001). Similarly, estimates of thermal inertia and Yarkovsky drift are common nowadays (Hammel et al., 2018; Greenberg et al., 2020) when the first studies were completed two decades ago only (Lagerros, 1996; Chesley et al., 2003).

Benefiting from these progresses is, however, complex: the fast-growing number of measured properties is spread over a myriad of articles. Machine-readable catalogs delivered by authors to the PDS or the CDS only represent the tip of the iceberg. Furthermore, there is a large heterogeneity in how SSOs are labeled (number, name, packed designation) and in how quantities are reported: masses \( M \) in kg or solar masses \( M_{\odot} \) or as GM product, albedo in linear or logarithmic scale for instance.

The sample size of individual articles may be small but their sum is large. In particular, some size-limited sample may be extremely valuable, such as results on a single target obtained during a spacecraft rendezvous for example. Compiling every estimate should hence not be overlooked by the community.

SsODNet.dataCloud compiles in a single database as many estimates as possible for a variety of SSO properties. Such centralization of data may appear anachronistic in current landscape of connections to remote databases, such as regularly done in the VO (Bayo et al., 2008). It is, however, required here. First, the remote databases do not exist. Second, owing to the issue of SSO naming, on-the-fly cross-matches between resources would be slow upon query. We chose here to place the workload on the server side, in an asynchronous process, to provide a fast service to users. Such a solution is already used for the ESA Gaia archive\(^{16}\), in which time-consuming cross-matches of Gaia catalog (Gaia Collaboration et al., 2016, 2018, 2021) with other common large catalogs (e.g., SDSS DR9, 2MASS, allWISE, Ahn et al., 2012; Skrutskie et al., 2006; Wright et al., 2010; Cutri et al., 2013) are already computed and stored (see details in Marrese et al., 2017).

3.2. Method

The design of the dataCloud is very simple: the parameters are grouped by collection of properties in SQL tables, e.g. diameter and albedo (as they are seldom derived independently), mass, thermal inertia, taxonomy, astrometry (the MPCAT-OBS database, MPC, 2021), etc. There are a few exceptions to this general scheme. The osculating elements of asteroids from the Minor Planet Center (MPC, Marsden, 1980) and the Lowell observatory (Bowell et al., 1994), as well as those of comets from the IMCCE (Rocher & Cavelier, 1996) are stored in separated tables. The Appendix A provides the list of collections composing the dataCloud ecosystem.

\(^{16}\) https://gea.esac.esa.int/archive/

4. Selection of the best estimates: ssoCard

Each entry of tables corresponds to a single determination of a parameter for a given target. Parameters are stored with their uncertainties, the method used to obtain them (see Appendix B), a selection flag (used to discriminate among estimates, see Section 4), and the bibliographic reference of the source of data. A given SSO, or bibliographic reference, may be repeated multiple times: some studies include many objects, and the same SSO may have been analyzed in multiple studies. The Figure 2 shows the distribution over time of the publications (currently 3007) used to build the dataCloud database. For convenience, a file compiling all the bibliographic references in bibtex format is available\(^{17}\).

A key aspect of the collections is the unique identifier for each SSO, built upon their name, used to identify them across tables. At every update of the database, the name of each SSO (as published by authors) is tested with SsODNet.quaero and updated upon ingestion. Hence, all properties are linked together using the most up-to-date designation.

For each parameter, we started the compilation from scratch, adding individually each bibliographic reference. The only exceptions to that are the masses and the spins. For both, we first ingested a previous compilation of data, from Carry (2012) and Warner et al. (2021) respectively.

4.1. Context

Among the hundreds of articles compiled in the dataCloud, a significant fraction report the same parameter for a given

\(^{17}\) https://ssp.imcce.fr/data/ssodnet.bib
SSO. A question then arises: how to choose a value, the best one, among others? A simple statistical averaging cannot address the question: some methods are intrinsically more precise than others, some are direct measurements while others are model-dependent. Moreover, uncertainties associated to values are often not accounting for possible biases, i.e., for external errors. This implies that the choice of the best value cannot entirely rely on the criteria of repeatability of the measurements.

The structure and format of data must also be addressed. The usual table format, i.e., rows and columns, appears unappropriated. Some SSOs have estimates of a wide variety of parameters (osculating elements, proper elements, diameter, mass, density, colors across many filters, taxonomy, and so forth), while others have a few parameters only (e.g., oscillating elements). Structuring the data in a flat 2D table implies that a vast majority of cells will be empty. With the current data in SsODNet, the filling factor of such a table would be ~15% only (see Section 5).

Furthermore, the association of data with meta-data (i.e., method, bibliographic reference, units) is also an issue in a table format. Consider that a human-readable bibliographic reference is composed of at least four fields (title, authors, year, bibcode), the number of columns will increase by a factor of four for each group of properties. In the current ecosystem of SsODNet.dataCloud, composed of 15 collections exposing 591 fields, it would imply a final table composed of 651 columns.

Considering all these elements, we choose to structure the parameters in a key-value data format allowing nested objects and arrays. We choose the open standard file format JSON (Bray, 2017). A XML-based format such as VOTable could have been suitable to include meta-data, but being verbose in nature it would significantly increase the volume of the data to exchange.

4.2. Method

The best estimate for each SSO property depends mainly on the method used to measure it: for example, a direct measurement from an in situ space mission can be considered as more valuable than an indirect determination based on telescopic observations acquired from the Earth. Similarly, a modern measurement is often more accurate than an earlier measurement owing to technological advances. On the other hand, an old value remains useful because it increases the temporal validity of the measurement, and can be unique. Finally, the accuracy (closeness to the true value) and precision (repeatability of the value) of measurements must be considered to choose a particular value among a data set, or to compute a statistical average.

For each set of properties, we defined a decision tree schematized by Figure 3. The methods are ordered in a preferential order. Among the ordered methods, the first available is chosen, and the weighted average \( \mu \) is computed from \( N \) multiple estimates \( x_i \) by the least squares estimator:

\[
\mu = \frac{\sum_{i=1}^{N} w_i x_i}{\sum_{i=1}^{N} w_i}
\]

(1)

where \( w_i = 1/\sigma_i^2 \) and \( \sigma_i = (\sigma_{+i} - \sigma_{-i})/2 \) is the arithmetic mean of the upper and lower uncertainties \( \sigma_{+i} \) and \( \sigma_{-i} \).

Similarly, the upper and lower uncertainties on \( \mu \) are computed as:

\[
\sigma_{\pm} = \frac{\sum_{i=1}^{N} w_i \sigma_{\pm i}^2}{\sum_{i=1}^{N} w_i}, \quad \text{with } w_i = 1/\sigma_i^2
\]

(2)

When the uncertainty of a value is unknown, we set it to 100% of the value to weight the mean.

At this stage, the \( N \) estimates used to compute the average may be less than the total number of estimates available. Every single entry in SsODNet.dataCloud has a selection flag (Section 3). Only three values are possible for this flag: -1, 0 (default), and 1. Any estimate with a selection flag of -1 is discarded from the computation of the best estimate. If an estimate is flagged to 1, it is considered to be the best estimate (we restrain from using it). The overwhelming majority of entries in dataCloud have a selection flag of 0.

We describe below how the preferential order is defined for each parameter, and provide the exhaustive order in Appendix C. Exceptions to this scheme of averaging are family membership, albedo, taxonomy, and orbital elements of SSOs.

4.2.1. Osculating elements

We store in SsODNet.dataCloud the complete catalogs of osculating elements of asteroids and dwarf planets proposed by the MPC (mpcorb, Marsden, 1980) and the Lowell Observatory (astorb, Bowell et al., 1994). Osculating elements are a consistent ensemble for each SSO. We thus do not select them individually, but as a group. We choose as primary source the astorb catalog for the sscocard, completed by elements from mpcorb for SSOs not listed in astorb.

For each SSO, we use its osculating elements (semi-major axis \( a \), inclination \( i \), and eccentricity \( e \)) to compute its Tisserand parameter (Tisserand, 1889) with Jupiter (\( T_J \)) and report it in the sscocard:

\[
T_J = \frac{a_J}{a} + 2 \cos i \sqrt{\frac{a}{a_J} (1 - e^2)}
\]

(3)

Article number, page 5 of 29
taking $a_J = 5.20336301 \text{ au}$ (mean J2000 orbital element).

### 4.2.2. Proper elements

Until recently, the only source of proper elements was the Asteroid - Dynamical Site\textsuperscript{19} (AstDyS, Knežević & Milani, 2003, 2012). The computations used either the analytical or numerical methods by Milani & Knežević (1990, 1994), Knežević & Milani (2000), and Knežević et al. (2002). More recently, Vinogradova (2019) introduced the empirical approach.

The most recent and largest update on asteroid proper elements is provided by the Asteroid Families Portal\textsuperscript{20} (Novakovic & Radovic, 2019). It thus prevails on the others, and we included it in the \texttt{dataCloud} to report proper elements of SSOs in \texttt{ssoCard}. As Jupiter Trojans and KBOs are not reported in this catalog, we complement it with the proper elements for these populations from AstDyS.

### 4.2.3. Families

The existence of asteroid families has been recognized over a century ago (Hirayama, 1918). Many authors have been working on the subject over the last decades, using mainly the Hierarchical Clustering Method (HCM, Zappala et al., 1990). A new method has recently emerged, called V-shape (Bolin et al., 2017).

As families are groups of SSOs, the selection is family-based in contrast with other parameters that are SSO-based. We set as reference the most-recent large-scale study (presently Vinogradova, 2019). All the families listed in the reference are considered valid, and SSOs belonging to these families have a family item in their \texttt{ssoCard} describing their membership.

We then complete these families with those reported in the other studies listed in \texttt{dataCloud}. We distinguish two cases. For articles studying families in general (e.g., Milani et al., 2014), we add the families not reported in the reference data set. The complexity arises from the fact that different authors may label the same family under different names (such as Minerva and Gefion being two names pointing at the same family, Milani et al., 2014; Nesvorny, 2015). We thus compute the fraction of common members between reported families. Whenever the overlap is smaller than 10%, the families are considered different. Alternatively, if one family is significantly smaller than the other (at most 20% in number of members), we include it to the list of families as it is likely a sub-family of the larger one.

For articles focusing on a single family (e.g., Tsirvoulis, 2019), we consider that they supersede the reference data set. If the family they describe is present in the reference data set, we replace the family membership of all SSOs in the family. If not, we simply add the new family (e.g., Delbo et al., 2019). We illustrate the dynamical families of in the asteroid belt available in \texttt{dataCloud} in Figure 4.

### 4.2.4. Pairs

Pairs of asteroids are objects on highly similar heliocentric orbits, first discovered by Vokrouhlický & Nesvorný (2008). They are similar to dynamical families with only two members, and are thought to be formed by rotational fission (Scheeres, 2007; Pravec et al., 2010). They are identified from the distance $d$ between their orbits (in m.s$^{-1}$):

$$
\left(\frac{d}{na}\right)^2 = k_a \left(\frac{\Delta a}{a}\right)^2 + k_e (\Delta e)^2 + k_i (\Delta \sin i)^2 + k_\Omega (\Delta \Omega)^2 + k_\omega (\Delta \omega)^2
$$

with $\Delta a$, $\Delta e$, $\Delta \sin i$, $\Delta \Omega$, $\Delta \omega$ the difference in semi-major axis, eccentricity, sine of inclination, longitude of the ascending node, and argument of perihelion; $n$ and $a$ the mean motion and semi-major axis of either component; and the numerical constants $k_a = 5/4$, $k_e = k_i = 2$, and $k_\Omega = k_\omega = 10^{-4}$ (Pravec et al., 2019). Backward integration has confirmed many of these pairs, with recent epochs in the past during which the two components were within their Hill sphere (see Žižka et al., 2016, for instance). These epochs are considered the ages of the pairs, time at which the two components became gravitationally unbound.

We consider all the pairs listed in the different sources compiled in the \texttt{dataCloud}. However, for the determination of the age, we select for the \texttt{ssoCard} the most recent determination over older studies.

### 4.2.5. Diameter

There are many different methods to estimate the diameter of a SSO. As a general scheme, we favor estimates obtained by a space mission (either flyby or rendez-vous, such as Belton et al., 1992) over all the others. Diameter estimates based on full 3D shape modeling (including direct measurement such as radar echoes, disk-resolved imaging, or stellar occultation) are then considered the most reliable (e.g., Hudson & Ostro, 1994; Carry et al., 2010; Viikinkoski et al., 2015; Bartzek & Dužiński, 2018). \textit{\texttt{dataCloud}}.

The next category of methods are convex shape models (generally obtained with the light-curve inversion method, Kaasalainen & Torppa, 2001) scaled a posteriori using another measurement (stellar occultation or mid-infrared flux, Đurech et al., 2011; Lagerros, 1996) or tri-axial ellipsoid (e.g., Drummond & Coiee, 1989; Drummond et al., 2014). These are followed by direct measurements limited to a single geometry, such as direct imaging (Marchis et al., 2006), stellar occultations (Dunham & Mallen, 1979), interferometry (Delbo et al., 2009) and broadening of the instrument point-spread function (Brown & Trujillo, 2004).

Then come the estimates from the analysis of mid-infrared fluxes with spherical models: STM (Lebofsky et al., 1986), FRM (Lebofsky & Spencer, 1989), NEATM (Harris & Davies, 1999), NESTM (Wolters & Green, 2009). Last are chosen the diameter estimates based on the absolute magnitude $H$ and the albedo $p_V$ (Section 4.2.6) when the latter was derived from the polarimetric phase curve of the SSO (e.g., Delbò et al., 2007).

We present the complete list of methods and their order for computing the best diameter estimate in Table C.1.

### 4.2.6. Albedo

In most cases, the albedo is derived by combining a diameter estimate ($D$) with the absolute magnitude $H$ at visible wavelength (more specifically in the Johnson V band,
hence the $p_V$ notation), using the canonical equation (Bowell et al., 1989):

$$p_V = \left( \frac{1329}{D} \right)^2 10^{-0.4H}$$

(5)

An albedo determination is thus closely linked with a diameter estimate, and this is why both quantities are reported in a single table in SsODNet.dataCloud. Because the absolute magnitude is constantly refined with the new photometry associated with the astrometry reported to the MPC, we compute $p_V$ using the latest available absolute magnitude $H$ and the best-estimate of the diameter (Section 4.2.5) using Equation 5. The uncertainties are computed as:

$$\sigma_{\pm,p_V} = p_V \sqrt{4 \left( \frac{\sigma_{\pm,D}}{D} \right)^2 + (0.4 \ln(10) \sigma_{\pm,H})^2}$$

(6)

Uncertainty on $H$ is seldom provided, and we use a default value of 0.3. The only exceptions to this approach are albedo estimated by space missions, or alternatively from polarimetric phase curve (see Table C.2), which are not recomputed. We present the albedo against proper orbital elements in Figure 4.

4.2.7. Masses

The determination of the mass of an SSO relies on measuring the effect of its gravitational attraction on another celestial body: either a spacecraft or another(s) SSO(s). The only exception to this is mass determination from the detection of Yarkovsky drift (Chesley et al., 2003).

The precision that can be achieved is strongly dependent on the type of interaction: with a spacecraft, a satellite in orbit, or long-distance encounters (Carry, 2012; Scheeres et al., 2015). We thus favor mass estimates achieved by radio science experiments during spacecraft encounters (Yeomans et al., 1997; Pätzold et al., 2011). Second come masses determined in binary systems, by studying the orbits of their moons (Merline et al., 1999; Pravec et al., 2006; Ostro et al., 2002; Vachier et al., 2012; Pajuelo et al., 2018).

Masses determined from SSO-to-SSO long-distance interaction: close encounters (Standish & Hellings, 1989; Sitdala & Granvik, 2020) and ephemerides (Baer & Chesley, 2008; Fienga et al., 2008) follow. Finally, for an SSO with a detected Yarkovsky drift (Vokrouhlický et al., 2015), it is possible to determine its mass, knowing many other parameters (diameter, albedo, obliquity, thermal inertia, Chesley et al., 2014).

We present the complete ordered list of methods for computing the best mass estimate in Table C.3.

4.2.8. Density

For each SSO with both a mass $M$ and a diameter $D$ estimates, we compute its density $\rho$ (kg.m$^{-3}$) and associated uncertainties:

$$\rho = \frac{M}{\pi \frac{D^3}{6}}$$

(7)

$$\sigma_{\pm,\rho} = \rho \sqrt{\left( \frac{\sigma_{\pm,D}}{D} \right)^2 + \left( \frac{\sigma_{\pm,M}}{M} \right)^2}$$

(8)

In some cases, the density can be determined without knowledge of either the mass or the volume. This is often the case of small binary asteroid systems studied by optical light-curves (Scheirich & Pravec, 2009; Carry et al., 2015). A few binary systems imaged by radar are also in this case (Ford et al., 2014). Last, the density can be derived from a detected Yarkovsky orbital drift (Rozitis & Green, 2014). We do not set preference of a method over another and average these estimates together. The distribution of density for a few selected taxonomic classes is presented in Figure 5.

4.2.9. Spin solutions

In most cases, the only available information on the spin of an SSO is its rotation period (often reported as synodic period). In some cases, however, the orientation of the spin axis has been determined, and we report its coordinates both in ECJ2000 (as reference time, longitude and latitude, see Kaasalainen & Torppa, 2001; Dreuch et al., 2010) and in EQJ2000 (as right ascension, declination, and the position of the prime meridian $W_0$ and $W'$, see Archinal et al., 2018).

Spin-vector coordinates determined with the light-curve inversion method (Kaasalainen & Torppa, 2001) are often degenerated with a mirror solution separated by 180° in ecliptic longitude. We use the selection flag (Section 3) to remove this ambiguity whenever one of the two spin solutions has been rejected posteriori (from comparison with stellar occultation or disk-resolved imaging for instance, Marchis et al., 2006; Dreuch et al., 2011). For each SSO with spin-vector coordinates, we compute its obliquity using these coordinates and its osculating elements (Section 4.2.1). We present the distribution of rotation period and obliquity against diameter in Figure 6.

Here again, solutions obtained by spacecraft encounters are favored over any others. They are followed by spin solutions obtained by 3D shape modeling techniques that include direct disk-resolved measurements (stellar occultations, disk-resolved images, e.g., Tanga et al., 2015; Vernazza et al., 2018; Shepard et al., 2018; Carry et al., 2019). Then come the 3D shape models, later scaled using complementary observations (mid-infrared fluxes, stellar occultations, disk-resolved images, Hanuš et al., 2013b; Dreuch et al., 2011). Spin solutions associated with convex shape models, generally with a mirrored spin solution, are then chosen (Hanuš et al., 2013a; Marciniak et al., 2018), followed by solutions obtained from tri-axial ellipsoids (Drummond & Coeke, 1989; Merline et al., 2013). Last are periods determined from light-curves, with or without constraints on the spin coordinates (Lagerkvist, 1978; Yeh et al., 2020). We refer to Table C.4 for a full listing of the order of preference.

The average spin coordinates are computed using Equation 1. However, as several ambiguous spin solutions may co-exist for a given SSO, we identify which estimates correspond to which spin solution using K-Means clustering (Lloyd, 1982), as provided by the scikit-learn21 python package (Pedregosa et al., 2011). We consider that up to four distinct spin solutions can be present, such as for (20) Massalia (Figure 7). Spin coordinates must be within 30° of the average to be included in a cluster. We set default uncertainties of 30° on spin coordinates whenever they are not specified by authors.

We use a similar approach, based on K-Means clustering for rotation periods. In this case the threshold to belong to

21 https://scikit-learn.org
Fig. 4: Distribution of families (first panel), albedo (second), colors (third, using a color-scheme similar to Parker et al. (2008) based on a code by Ivezić et al. (2014)), and taxonomy (fourth) against proper elements (semi-major axis and sine of inclination). The number of plotted objects is reported in each panel.

a solution is set to 0.2 h. The default uncertainty is set to 1 h.

4.2.10. Colors

Stricto sensu, the colors of SSOs are observable and not derived properties. We nevertheless compile colors of SSOs in SsODNet.dataCloud, with the same rationale as for derived properties: many colors are available but spread over many studies (e.g., Dandy et al., 2003; Snodgrass et al., 2010; Dumintru et al., 2018), often not in machine-readable format. Furthermore, colors can be used for taxonomic determination (Carvano et al., 2010; DeMeo & Carry, 2013).

Several ancillary information for contextualization are recorded (Table A.3), such as the observing time, the source of measurement (plain English description and IAU Observatory code\(^\text{22}\) if available). The filters used to compute the colors are identified with the unique identifier of the

\(^{22}\text{https://minorplanetcenter.net/iau/lists/ObsCodesF.html}\)
Fig. 5: Kernel density estimate (KDE) of the density of the C, S, X, and B complexes. The bimodal distribution of X-types highlights the P and M sub-classes (average $p_V$ of 0.044 and 0.129, below and above 2000 kg.m$^{-3}$, respectively). Similarly, Pallas is the sole contributor to high-density B-types.

SVO Filter Service\(^\text{23}\) providing transmission curves and zero points (Rodrigo et al., 2012; Rodrigo & Solano, 2020). Similarly, we record in which system the photometry is reported (Vega, AB, or ST).

The selection of best estimates is based on the time difference $\Delta t$ between the observation of the two filters, and how the color was computed. We favor (Table C.5) colors computed as a difference of apparent magnitudes from phase functions in each filter (Mahlke et al., 2021; Alvarez-Candal et al., 2021). In that case, we report the most-recent published value.

Colors computed as a difference of apparent magnitudes but corrected for light-curve variation (Monnert et al., 2016; Erasmus et al., 2019) follow. Last are the simple difference of apparent magnitudes (Popescu et al., 2018; Sergeyev & Carry, 2021). Whenever several estimates of the same color with the two latter methods are reported we compute their average as in Equation 1, with the following weight to account for time difference: $w_i = 1/\sigma_i^2 + 1/\Delta \tau_i^2$.

Whenever the information on $\Delta t$ is missing, we set it to 1 h.

Last but not least, filter transmissions are different in each facility. For a given color (e.g., $g$-$i$), the values from different observatories may differ (e.g., between the Sloan Digital Sky Survey and SkyMapper, see Fig. 9 in Sergeyev et al., 2022). We do not merge colors obtained with different filter sets ($\text{SDSS.g-SLOAN/SLOAN.i}$ vs. SkyMapper/SkyMapper.$g$-SkyMapper/SkyMapper.$i$), but rather report the most precise. An example of colors is shown in Figure 4.

4.2.11. Phase function

Phase functions describe the evolution of brightness with the phase angle (once corrected from the Sun-target and target-observer distances). The absolute magnitude reported together with osculating elements (Section 4.2.1) is computed using the historical two-parameter HG phase function (Bowell et al., 1989), in which $G$ is generally assumed to be 0.15. This function has been shown to deviate from observed photometry at low and high phase angle, and a three-parameter HG$_1$G$_2$ function has been proposed (Muinonen et al., 2010). We collect in the dataCloud and report in ssoCard these parameters. Because phase functions are wavelength dependent (Sanchez et al., 2012; Mahlke et al., 2021), we associate these parameters to the filter in which they were derived, here again using the unique identifier of the SVO Filter Service (Rodrigo et al., 2012; Rodrigo & Solano, 2020).

A parameterized version of the phase function has been proposed for low-accuracy data (with two parameters, HG$_{12}$, later refined as HG$_{12}$, Penttilä et al., 2016). We, however, stick to HG$_1$G$_2$ parameters only, as they have been shown to convey taxonomic and albedo information (Shevchenko et al., 2016; Mahlke et al., 2021).

4.2.12. Taxonomy

The taxonomy is often used as a proxy for composition in statistical studies of populations (Park et al., 2008; DeMeo & Carry, 2014; Binzel et al., 2019; Hasegawa et al., 2021). The complexity of compiling taxonomic classes is manifold. First, several taxonomies (as classification

\(^{23}\) http://svo2.cab.inta-csic.es/theory/fps/
schemes) have been developed and used by the community, such as Tedesco et al. (1989), Tholen (1989), Bus & Binzel (2002), DeMeo et al. (2009), and Mahlke et al. (2022). Second, there is a great diversity in the potential combinations of these schemes with observing techniques (multi-filter photometry and spectroscopy, Xu et al., 1995; Carry et al., 2016), and wavelengths (visible only, near-infrared only, and both ranges, Carvano et al., 2010; Popescu et al., 2018; Marss et al., 2014).

We present in Figure 8 the decision tree we apply to select the most relevant taxonomy for a given SSO. As a general rule, results from spectroscopy are favored over results from multi-filter photometry. Within each observing technique, results using both visible and near-infrared are favored, then those based on infrared only, and finally on visible only. Once the observing technique and wavelength range is selected, there may be several taxonomic schemes available, and we chose in order the Mahlke, Bus-DeMeo, SMASS, Bus, and Tholen taxonomy.

In an attempt to homogenize all the classes that have been reported for a given object, we also group similar classes under the term “complex”, following the associations listed in Table C.8. We give an example of the orbital distribution of these complexes in Figure 4.

4.2.13. Thermal properties

Mid-infrared fluxes are often used to determine the diameter of an SSO (Section 4.2.5), from simple thermal models such as the NEATM (Harris & Davies, 1999). More complex thermal models (referred to as Thermophysical models, TPM, Lagerros, 1996) can also be used, but required additional information on the object, such as spin, 3D shape. A parameter of these TPM is the thermal inertia (in J.s^-1/2.K^-1.m^-2) controlling the resistance of the surface to changes of temperature.

Thermal inertia determination from spacecrafts are favored (Capria et al., 2014), then those determined from TPM using a priori knowledge on the spin and shape (Matter et al., 2013; O’Rourke et al., 2012), and finally TPM applied on spheres (Müller et al., 2013) as listed in Table C.6. Thermal inertia (Γ) is a function of heliocentric distance (Vasavada et al., 1999; Rozitis et al., 2018). We thus report the thermal inertia at 1 au (Γ0) from the Sun in the ssoCard, using the following relation

\[ Γ = Γ_0 r_H^α \]  (9)

where \( r_H \) is the heliocentric distance at the time of the observations. We take \( α = -3/4 \) following Delbo et al. (2015). We present the distribution of thermal inertia against diameter in Figure 9.

4.2.14. Yarkovsky drift

While the orbital drift due to the delayed thermal emission by asteroid surface is extremely small (of the order of 10^-4 au/Myr, Vokrouhlický et al., 2015), it has been detected for the first time almost two decades ago (Chesley et al., 2003). We favor detection that include both optical and radar observations (Farnocchia et al., 2014, for instance) over those using optical only (e.g., Del Vigna et al., 2018). Last (Table C.7) are estimated based on the age of dynamical families (Carruba et al., 2017).

Some authors report the semi-major axis drift \( \dot{a} \) (Nugent et al., 2012) while others report the transverse acceleration \( A_2 \) (Greenstreet et al., 2019) like in cometary dynamical models (Marsden et al., 1973). We report both parameters in the ssoCard, using the following equation from Farnocchia et al. (2013) to convert between quantities:

\[ \dot{a} = \frac{A_2}{a^2 (1 - e^2) \pi n} \int_0^{2\pi} (1 + e \cos f) df \]  (10)

with \( a \) the semi-major axis, \( e \) the eccentricity, and \( n \) the mean motion (Section 4.2.1).

5. Summary for all SSOs: ssoBFT

The ssoBFT service described in previous section provides a convenient access to best-estimates of many parameters, but limited to a single SSO. The last service composing SsODNet thus provides a broad and flat table (ssobft) that compiles all the parameters of the ssoCard for all SSOs. This table is very large (over 591 fields for 1 223 984 SSOs, about 2.1 Gb). Yet, most fields are empty (i.e., there is no estimate of the given parameter for this SSO), resulting in only a 14.6% filling factor.

We propose the ssobft as an enhanced character separated values (eCSV) and an Apache parquet files for users interested in the statistical properties of the asteroid population. These files can be downloaded at static urls (eCSV, parquet). We also provide this table to the CDS to ensure its fully VO-compliant access.

6. Accessing the services: SsODNet & rocks

We offer several access interfaces to the SsODNet service, described below.

6.1. REST interface

The quaero representational state transfer (REST) API is a low-level interface dedicated to developers. It is designed to offer an easy-to-use and fast solution to search for planetary objects (ssobft and search methods), to resolve their designations (resolver method), or to be used as an auto-completion mechanism for names (instant search method) into Web forms and applications connected to the Internet. In the framework of the Virtual Observatory, no standard protocol nor technical specification is quite capable of designing a fast-search engine. Thus the core of SsODNet name resolver does not follow current VO standard. Nevertheless, the underlying technology and the API we have chosen being intrinsically interoperable, the quaero service can easily be included in any VO ecosystem.

End-point: https://api.ssoonet.imcce.fr/quaero/1/Doc: https://doc.ssoonet.imcce.fr/quaero.html

24 https://github.com/astropy/astropy-APEs/blob/main/APE6 rst
25 https://parquet.apache.org/
26 https://sso.imcce.fr/data/ssobft-latest.ecsv.bz2
27 https://sso.imcce.fr/data/ssobft-latest.parquet
Fig. 8: Decision tree for taxonomic classes. Classes based on spectroscopy are favored upon those based on broad-band photometry only. Similarly data sets covering the full VISNIR wavelength range are favored over NIR only, itself preferred to VIS only. Finally, for classification based on similar data sets, the Mahlke scheme is preferred over Bus-DeMeo, Bus, SMASS, and Tholen schemes.

Fig. 9: All 1681 SSOs with a thermal inertia above 1 SI (gray), the 419 with a SNR above 3 (black), and a linear regression on the latter of equation \( \log(\Gamma) = 2.5 - 0.29 \log(D) \), similar to the recent work of Hung et al. (2022).

6.2. Web-service interface

We provide a Web-service interface, built upon XML and SOAP technology, that allows a full interaction with SsODNet through several methods:

- resolver: to identify SSO (high level API)
- datacloud: to retrieve all known values of SSO properties
- ssoCard: to retrieve the best estimates of SSO properties

The user can simply post a request to the method end-points to gather corresponding data, using a data transfer program such as wget or curl. More advanced users can implement the SOAP Web service to ensure an application-to-application communication between SsODNet and a software or a public Web page.

SsODNet server: https://ssp.imcce.fr/webservices/ssodnet/ssodnet.php
Public interface: https://ssp.imcce.fr/webservices/ssodnet/ssodnet.php?wsdl
Doc: https://ssp.imcce.fr/webservices/ssodnet/

6.3. Web form interface

The easiest way to search for a SSO and to quickly consult its properties may be to use SsODNet dedicated Web form. The best estimates of the physical and dynamic properties (the ssoCard) are displayed in a comprehensive manner, together with bibliographic references. We also provide links to all values (i.e., dataCloud entry for each property of the SSO), and to the subset used to compute the best estimates (as defined by the decision trees, see Section 4).

Web form: https://ssp.imcce.fr/forms/ssocard/
Doc: https://ssp.imcce.fr/forms/ssocard/doc

6.4. Python interface: rocks

We provide a python interface to SsODNet named rocks. It offers a programmatic entry point both for data exploration and data processing. The interaction with the SsODNet repositories is asynchronous and results are cached on the user-side, providing a responsive user experience.

Sources: https://github.com/maxmahlke/rocks
Doc: https://rocks.readthedocs.io

Data exploration is accessible via the command line interface of rocks in a straight-forward, uniform syntax:

\$ rocks [command|parameter] [asteroid_identifier]

Here, parameter can be any key from the ssoCard or dataCloud cataloge, and the asteroid_identifier is any identifier that can be resolved by quaoer. The result of the query is printed in the console. Commands like id and info serve to identify an asteroid and to print the asteroid’s ssoCard.

\$ rocks id "1975 XP"
(234) Barbara
\$ rocks taxonomy Barbara
L
\$ rocks diameter barbara
46.3 +- 5.0 km
\$ rocks albedo 234
0.187 ± 0.2839

An overview of all compiled literature values is printed when requesting the plural of the parameters. This is possible for all parameters which have dataCloud entries, e.g. albedo, mass, taxonomy.

```
$ rocks taxonomies ceres
| class | method | scheme | shortbib |
+-------+--------+-----------+-----------------+
| G     | Phot   | Tholen    | Tholen+1989     |
| C     | Spec   | Bus       | Bus&Binzel+2002 |
| C     | Spec   | Bus       | Lazzaro+2004   |
| C     | Spec   | Lazzaro+2004 |
| C     | Spec   | Bus-DeMeo | DeMeo+2009     |
| C     | Spec   | Bus       | Fornasier+2014b|
| C     | Spec   | Tholen    | Fornasier+2014b|
| C     | Spec   | Bus-DeMeo | Sergeyev+2022  |
| C     | Spec   | Mahlke    | Mahlke+2022    |
+-------+--------+-----------+-----------------+
```

Data processing is facilitated for python scripts using the rocks package. The main entry point is the rocks.Rock class, where each instance reflects a unique asteroid. The asteroid parameters are accessible as class attributes via the dot notation, which again leads to an intuitive syntax:

```python
>>> import rocks
>>> vesta = rocks.Rock(4)
>>> vesta.albedo.value
0.38
>>> vesta.albedo.error.min_
-0.04
>>> vesta.albedo.error.max_
0.04
>>> vesta.albedo.description
'Geometrical albedo in V band'
```

The asynchronous interaction with the locally cached data and the remote SsODNet repositories allow for a fast analysis process without the use of resource-intensive multiprocessing or multi-threading strategies. To provide an estimate of the execution times, we identify all asteroids in the SDSS Moving Object Catalog DR1 and retrieve their ssoCard. The catalog contains observations of 10,585 unique minor bodies, largely referred to by designations which are no longer the main identifier of the object. Using a combination of quaero queries and a local asteroid name-number-designation index, rocks identifies all objects within 2.5s. The ssoCards are retrieved within 320s from SsODNet, about 30ms per asteroid. rocks then performs data validation and deserialization (i.e. converting the JSON server response into a python object) within 120s, about 11ms per asteroid. A second execution of the analysis script would benefit from the locally cached ssoCards, rendering any request to SsODNet obsolete.

rocks can be installed from the python package index (PyPI) under the package name space-rocks. The reader is referred to the online documentation for a guide on getting started and tutorials to achieve more advanced data processing results. rocks is actively developed and maintained by the authors.

7. Future developments

We foresee several lines of development for the SsODNet service: data compilation and curation, expansion of the set of parameters and types of SSOs, and development of the interface.

Data compilation: First and foremost, we will continue to compile data into the dataCloud, aiming at completeness for the listed parameters. Indeed, it is the building block of the ssoCard and the ssoBFT, that are automatically generated from the entries in the dataCloud. On the other hand, quaero has been working and been updated weekly for several years, following the growing list of SSOs listed by the MPC. So a continuous scientific monitoring of publications is required for the service.

We thus welcome any feedback, especially on data sources that may be missing, or erroneous entries. While we conducted multiple checks on the data included in SsODNet, some typographical errors may lurk in the unprecedented size of the data compilation. We will happily include sources that were not added in the present release of the service, and correct entries.

Furthermore, SsODNet can be used by any group or researcher to publish regularly-updated data: a simple file (VOTable, csv, ...) with sufficient metadata at a static url can be used as a source to be included, without requiring a server or a database with a Web Service to be maintained.

Set of parameters: The set of parameters currently available in SsODNet is already large, covering dynamical, surface, and physical properties (Table A.1). There are, however, other parameters of interest that will be added to the dataCloud (and hence ssoCard and ssoBFT), such as the source region probabilities for near-Earth objects (Granvik et al., 2017) and their Minimal Orbital Intersection Distance (MOID, Marsden, 1993) with planets, activity for asteroids and Centaurs (Hsieh & Jewitt, 2006; Jewitt, 2009), radar albedos (Neeley et al., 2014). Additional computed parameters can also be added in ssoCard, such as surface gravity, or escape velocity.

Types of SSOs: The present release of SsODNet focuses on asteroids, because they are the prime targets of study of the authors. The service was nevertheless designed to cope with all classes of SSOs: comets, planets, satellites, and interstellar objects. For instance, quaero already deals with the designation of all these categories.

We thus welcome partnership with everyone willing to contribute to build this community database. Beside the collection and curation of data, a set of parameters relevant for these celestial bodies must be defined (e.g., non-gravitational acceleration for comets, libration amplitude and frequency for satellites), together with decision trees

---

28 http://faculty.washington.edu/ivezic/sdssmoc/sdssmoc.html

29 https://rocks.readthedocs.io
to estimate the best parameters. \textit{SsODNet} has been envisioned as a service to the community, and any contribution will benefit to everyone.

**User interface:** \textit{SsODNet} is mainly a machine-machine service, allowing on-the-fly data retrieval. Both \texttt{quaero} and \texttt{ssoCard} are designed to cope with constant queries. The \texttt{dataCloud} entries for a given SSO can also be dumped easily, and the \texttt{ssoBFT} downloaded as a whole.

We plan to develop more advanced possibilities to query the data, both in \texttt{dataCloud} and \texttt{ssoBFT}. Users may be interested by searching entries from a given bibliographic reference, rather than for a specific SSO for instance. Similarly, users may be interested in a subset of the \texttt{ssoBFT} only (e.g., some specific parameters only for SSOs fulfilling certain conditions). While the latter is possible with TAP on the version of the \texttt{ssoBFT} hosted at the CDS, the former development on the server side of \textit{SsODNet}.

8. Conclusions

We present a new Web Service, \textit{SsODNet}, which provides a convenient solution to the issues of SSO identification and compilation of properties. It consists in a suite of applications, each with a programming interface: \texttt{quaero} for name resolution, \texttt{dataCloud} compiling SSO properties, \texttt{ssoCard} providing the set of best estimates for each SSO, and \texttt{ssoBFT} compiling the latter for all SSOS. These entry points deliver JSON as native outputs. We release a python interface to these services: \texttt{rocks}, available in the python package index (PyPI). \textit{SsODNet} is fully operational. The name resolver \texttt{quaero} is updated weekly to follow SSO discoveries. We plan on monthly updates for the others applications, following compilation of data from continuous monitoring of new publications. Future evolution of the service includes an extension of the suite of properties and classes of SSOs, and an advanced query interface to retrieve large corpus of data.

Acknowledgements. This research has made use of the SVO Filter Profile Service supported from the Spanish MINECO through grant AYA2017-84089. This research has made use of the \texttt{scikit-learn} python package (Pedregosa et al., 2011). We did an extensive use of the VO TOPCAT software (Taylor, 2005). Thanks to all the developers and maintainers.

We would like to thank J. Masiero, F. E. DeMeo, and F. Spoto for discussions that led to the current decision trees used in \textit{SsODNet}.

References

Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2012, ApJS, 203, 21
Alvarez-Candal, A., Benavidez, P. G., Campo Bagatin, A., & Santana-Ros, T. 2021, arXiv e-prints, arXiv:2110.06021
Archinal, B. A., Acton, C. H., A'Hearn, M. F., et al. 2018, Celestial Mechanics and Dynamical Astronomy, 130, 22
Baer, J. & Chesley, S. R. 2008, Celestial Mechanics and Dynamical Astronomy, 100, 27
Bailey, S. I. & Pickering, E. C. 1913, Annals of Harvard College Observatory, 72, 165
Bartczak, P. & Dudziński, G. 2018, MNRAS, 473, 5050
Bayo, A., Rodrigo, C., Barrado Y Navascués, D., et al. 2008, A&A, 492, 277
Bell, J. F., Owensby, P. D., Hawke, B. R., & Gaffey, M. J. 1988, in Lunar and Planetary Science Conference, Vol. 19, Lunar and Planetary Science Conference, 57
Belskaya, I. N. & Shevchenko, V. G. 2000, Icarus, 147, 94
Belton, M. J. S., Veverka, J., Thomas, P., et al. 1992, Science, 257, 1647
Berthier, J., Hestroffer, D., Carry, B., et al. 2008, LPI Contributions, 1405, 8374
Berthier, J., Vachier, F., Thuillot, W., et al. 2006, in Astronomical Society of the Pacific Conference Series, Vol. 351, Astronomical Data Analysis Software and Systems XV, ed. C. Gabriel, C. Arviset, D. Piana, & S. Enrici, 367–70
Binzel, R. P., DeMeo, F. E., Turtelboom, E. V., et al. 2019, Icarus, 324, 41
Binzel, R. P., Xu, S., Bus, S. J., et al. 1993, Science, 262, 1541
Bolin, B. T., Delbo, M., Morbidelli, A., & Walsh, K. J. 2017, Icarus, 282, 290
Bowell, E., Chapman, C. R., Gradie, J. C., Morrison, D., & Zellner, B. 1978, Icarus, 35, 313
Bowell, E., Hapke, B., Domingue, D., et al. 1989, Asteroids II, 524
Bowell, E., Muinonen, K., & Wasserman, L. H. 1994, in Asteroids, Comets, Meteors 1993, ed. A. Milani, M. di Martino, & A. Cellino, Vol. 160, 477–481
Bray, T., E. 2017
Brown, M. E. & Trujillo, C. A. 2004, AJ, 127, 2413
Bus, S. J. & Binzel, R. P. 2002, Icarus, 158, 146
Capria, M. T., Tosi, F., De Sanctis, M. C., et al. 2014, Geo-
Phys. Res. Lett., 41, 1438
Carruba, V., Vokrouhlický, D., & Nesvorný, D. 2017, MNRAS, 469, 4400
Carry, B. 2012, Planet. Space Sci., 73, 98
Carry, B., Dumas, C., Kaasalainen, M., et al. 2010, Icarus, 205, 460
Carry, B., Matter, A., Scheirich, P., et al. 2015, Icarus, 248, 516
Carry, B., Solano, E., Eggl, S., & DeMeo, F. E. 2016, Icarus, 268, 340
Carr, L., Vachier, F., Berthier, J., et al. 2019, A&A, 623, A132
Carvano, J. M., Haeselmann, P. H., Lazzaro, D., & Mothé-Diniz, T. 2010, A&A, 510, A43
Cellino, A., Hestroffer, D., Lu, X. P., & DeMeo, F. E. 2019, Icarus, 328, 1739
Cruikshank, D. P. & Morrison, D. 1973, Icarus, 20, 477
Cutri, R. M., Wright, E. L., Conrow, T., et al. 2013, Explanatory Supplement to the AllWISE Data Release Products, Explanatory Supplement to the AllWISE Data Release Products
Dandy, C. L., Fitzsimmons, A., & Collader-Brown, S. J. 2003, Icarus, 163, 363
Davidsson, B. J. R., Gutiérrez, P. J., & Rickman, H. 2007, Icarus, 187, 306
Del Vigna, A., Faggiani, L., Milan, A., et al. 2018, A&A, 617, A61
Del Vigna, A., Roa, J., Farnocchia, D., et al. 2019, A&A, 627, L11
Delbo, M., Avellidou, C., & Morbidelli, A. 2019, A&A, 624, A69
Denz, M., Cellino, A., & Tedesco, E. F. 2007, Icarus, 188, 266
Delbo, M., Ligori, S., Matter, A., Cellino, A., & Berthier, J. 2009, ApJ, 694, 1228
Delbo, M., Mueller, M., Emery, J. P., Rozitis, B., & Capria, M. T. 2015, Asteroid Thermophysical Modeling, 107–128
Delbo, M., Tanga, P., Carry, B., Ordenovic, C., & Bottein, P. 2018, in Asteroids, Comets, and Meteors: ACM 2018
DeMeo, F. E., Binzel, R. P., Slivan, S. M., & Bus, S. J. 2009, Icarus, 202, 160
DeMeo, F. E. & Carry, B. 2013, Icarus, 226, 723
DeMeo, F. E. & Carry, B. 2014, Nature, 505, 629
Devogèle, M., Moskovitz, N., Thirouin, A., et al. 2019, AJ, 158, 196
Drummond, J. D. 2000, in NATO Advanced Study Institute (ASI) Se-
ries C, Vol. 551, Laser Guide Star Adaptive Optics for Astronomy, ed. N. Ageorges & C. Dainty, 243
Drummond, J. D., Carry, B., Merline, W. J., et al. 2014, Icarus, 236, 28
Drummond, J. D. & Coxe, W. J. 1989, Icarus, 73, 323
Drummond, J. D., Coxe, W. J., Hege, E. K., & Strixtmatter, P. A. 1985, Icarus, 61, 132
Dumitru, B. A., Birlan, M., Sonka, A., Colas, F., & Nedelcu, D. A. 2018, Astronomische Nachrichten, 339, 198
Dunham, D. W. & Mallen, G. 1979, Rev. Mexicana Astron. Astrofis., 4, 205
Drucha, J., Sidorin, V., & Kaasalainen, M. 2010, A&A, 513, A46
Erasmus, N., McNeill, A., Mommert, M., et al. 2019, ApJS, 242, 15

Article number, page 13 of 29
# Appendix A: Collections available in SsODNet.dataCloud

Table A.1: Description of the collections included in SsODNet.dataCloud.

| Name            | Description                              | $N$     | $N_{SSO}$ | Desc. | Reference                  |
|-----------------|------------------------------------------|---------|-----------|-------|----------------------------|
| astorb          | Lowell orbits of asteroids               | 1 078 203 | 1 078 203 | A.2   | Bowell et al. (1994)       |
| colors          | Compilation of colors                    | 4 793 938 | 428 339   | A.3   | 29 references              |
| cometpro        | IMCCE orbits of comets                   | 1 613    | 1 613     | A.4   | Rocher & Cavelier (1996)   |
| density         | Density estimates                        | 49       | 29        | A.5   | 26 references              |
| diamalbedo      | Diameter & albedo estimates             | 261 396  | 149 375   | A.6   | 205 references             |
| families        | Dynamical families                       | 493 364  | 261 832   | A.7   | 9 references               |
| masses          | Mass estimates                           | 2 170    | 422       | A.8   | 165 references             |
| mpcatobs        | MPC catalog of observations              | 341 772 068 | 1 674 187 | A.9   | MPC (2021)                 |
| mpcorb          | MPC orbits of asteroids                  | 1 223 386 | 1 223 386 | A.10  | Marsden (1980)             |
| pairs           | Asteroid pairs                           | 340      | 236       | A.11  | 12 references              |
| phase_function  | Parameters of phase functions            | 330 279  | 227 888   | A.12  | 4 references               |
| proper_elements | Proper elements of asteroids             | 799 878  | 799 878   | A.13  | Novakovic & Radovic (2019) |
| spin            | Spin solutions                           | 47 541   | 28 951    | A.14  | 2 775 references           |
| taxonomy        | Taxonomic classes                        | 274 322  | 140 713   | A.15  | 208 references             |
| thermal_properties | Thermal inertia estimates                | 4 510    | 2 109     | A.16  | 57 references              |
| yarkovsky       | Yarkovsky drifts                         | 826      | 578       | A.17  | 17 references              |

Total 351 083 883 | 1 223 984 | 3007 references

For each collection we list the number of entries ($N$), number of SSOs ($N_{SSO}$), the reference to a table describing its fields (Desc.), and the number of included bibliographic references.

Table A.2: Description of the fields in the collection astorb of the dataCloud.

| #   | Field           | Type | Description                                                |
|-----|-----------------|------|------------------------------------------------------------|
| 1   | num             | int  | SSO IAU Number                                             |
| 2   | name            | varchar | SSO name                                         |
| 3   | orbit_computer  | varchar | Orbit computer                                       |
| 4   | H               | double | Absolute magnitude (mag)                               |
| 5   | G               | double | Slope parameter (Bowell et al., 1989)                   |
| 6   | B_V             | double | B-V color (mag) from Tedesco (1989)                     |
| 7   | IRAS_diameter   | double | IRAS diameter (km) from Tedesco et al. (1989)           |
| 8   | IRAS_class      | varchar | IRAS taxonomic classification from Tedesco et al. (1989) |
| 9   | note_1          | int  | Categories of planet-crossing asteroids                  |
| 10  | note_2          | int  | Assumptions for orbit computation                        |
| 11  | note_3          | int  | Asteroids observed during the course of major surveys    |
| 12  | note_4          | int  | Indication from MPC critical-list of numbered asteroids  |
| 13  | note_5          | int  | Discoveries at Lowell Observatory and related discoveries|
| 14  | note_6          | int  | Rank for Lowell collaborative program of astrometry       |
| 15  | orbital_arc     | int  | Orbital arc spanned by observations used in orbit computation (days) |
| 16  | number_observation | int  | Number of observations used in orbit computation        |
| 17  | yy_osc          | int  | Year of the epoch of osculation                         |
| 18  | mm_osc          | int  | Month of the epoch of osculation                         |
| 19  | dd_osc          | int  | Day of the epoch of osculation                           |
Table A.2: continued.

| #  | Field                  | Type      | Description                                                                 |
|----|------------------------|-----------|-----------------------------------------------------------------------------|
| 20 | mean_anomaly           | double    | Mean anomaly (deg)                                                          |
| 21 | perihelion_argument    | double    | Argument of perihelion (deg) in ECJ2000.0                                    |
| 22 | node_longitude         | double    | Longitude of ascending node (deg) in ECJ2000.0                               |
| 23 | inclination            | double    | Inclination (deg) in ECJ2000.0                                              |
| 24 | eccentricity           | double    | Eccentricity                                                                |
| 25 | semi_major_axis        | double    | Semi-major axis (au)                                                         |
| 26 | YY_calculation         | int       | Year of the date of orbit computation                                       |
| 27 | MM_calculation         | int       | Month of the date of orbit computation                                       |
| 28 | DD_calculation         | int       | Day of the date of orbit computation                                         |
| 29 | CEU_value              | double    | Absolute value of the Current 1-σ Ephemeris Uncertainty (CEU, in arcsec)     |
| 30 | CEU_rate               | double    | Rate of change of CEU (arcsec/day)                                          |
| 31 | CEU_yy                 | int       | Year of the date of CEU                                                     |
| 32 | CEU_mm                 | int       | Month of the date of CEU                                                    |
| 33 | CEU_dd                 | int       | Day of the date of CEU                                                      |
| 34 | PEU_value              | double    | Next Peak Ephemeris Uncertainty (PEU) from date of CEU (arcsec)             |
| 35 | PEU_yy                 | int       | Year of the date of occurrence of the PEU                                   |
| 36 | PEU_mm                 | int       | Month of the date of occurrence of the PEU                                  |
| 37 | PEU_dd                 | int       | Day of the date of occurrence of the PEU                                    |
| 38 | GPEU_fromCEU           | double    | Greatest PEU in 10 years from date of CEU (arcsec)                          |
| 39 | GPEU_yy                | int       | Year of the date of occurrence of the GPEU                                  |
| 40 | GPEU_mm                | int       | Month of the date of occurrence of the GPEU                                 |
| 41 | GPEU_dd                | int       | Day of the date of occurrence of the GPEU                                   |
| 42 | GPEU_fromPEU           | double    | Greatest PEU in 10 years from date of next PEU (arcsec)                      |
| 43 | GGPEU_yy               | int       | Year of the date of occurrence of the GPEU from PEU                         |
| 44 | GGPUE_mm               | int       | Month of the date of occurrence of the GPEU from PEU                        |
| 45 | GGPUE_dd               | int       | Day of the date of occurrence of the GPEU from PEU                          |
| 46 | jd_osc                 | double    | JD of the epoch of osculation                                                |
| 47 | px                     | double    | x component of the EQJ2000 heliocentric position vector (au)                |
| 48 | py                     | double    | y component of the EQJ2000 heliocentric position vector (au)                |
| 49 | pz                     | double    | z component of the EQJ2000 heliocentric position vector (au)                |
| 50 | vx                     | double    | x component of the EQJ2000 heliocentric velocity vector (au/d)              |
| 51 | vy                     | double    | y component of the EQJ2000 heliocentric velocity vector (au/d)              |
| 52 | vz                     | double    | z component of the EQJ2000 heliocentric velocity vector (au/d)              |
| 53 | mean_motion            | double    | Mean motion (deg/d)                                                         |
| 54 | orbital_period         | double    | Orbital period (d)                                                          |
| 55 | iddataset              | int       | Bibliographic unique reference                                              |

Fields follow the original ASTORB data (Bowell et al., 1994), and we refer to the online documentation for further details on each field (https://asteroid.lowell.edu/main/astorb/).

Table A.3: Description of the fields in the collection colors of the dataCloud.

| #  | Field     | Type | Description                           |
|----|-----------|------|---------------------------------------|
| 1  | num       | int  | SSO IAU Number                        |
| 2  | name      | varchar | SSO name                             |
| 3  | color     | varchar | Name of the color (e.g, B-V)         |
| 4  | value     | double | Value of the color                    |
| 5  | uncertainty | double | Uncertainty on the color              |
| 6  | facility  | varchar | Source of data (telescope, survey)   |
| 7  | observer  | varchar | Observer IAU code                    |
| 8  | epoch     | double | Epoch of observation (JD)             |
Table A.3: continued.

| #  | Field               | Type   | Description                                                                 |
|----|---------------------|--------|-----------------------------------------------------------------------------|
| 9  | delta_time          | float  | Time difference between filters (s)                                          |
| 10 | color_type          | varchar| Description of the method (Table B.1)                                      |
| 11 | id_filter_1         | varchar| First filter unique identifier (SVO filter service, Rodrigo et al., 2012)  |
| 12 | id_filter_2         | varchar| Second filter unique identifier (SVO filter service, Rodrigo et al., 2012) |
| 13 | phot_sys            | varchar| Photometric system (Vega, AB, ST)                                           |
| 14 | selection           | int    | Selection flag (Section 4)                                                  |
| 15 | iddataset           | int    | Bibliographic unique reference                                              |

Table A.4: Description of the fields in the collection cometpro of the dataCloud.

| #  | Field               | Type   | Description                                                                 |
|----|---------------------|--------|-----------------------------------------------------------------------------|
| 2  | note                | int    | Number of the note associated with the comet                                |
| 3  | updated             | date   | Date of update (DD/MM/YYYY)                                                 |
| 4  | name                | varchar| IAU code of the comet                                                        |
| 5  | iau_name            | varchar| IAU name of the comet                                                        |
| 6  | author              | varchar| Orbit computer                                                              |
| 7  | epoch               | double | Reference epoch of the orbit (JD)                                            |
| 8  | force_relat         | int    | Relativity effect of the Sun taken into account (1) or not (0)              |
| 9  | nb_observations     | int    | Number of observations used in orbit computation                            |
| 10 | sigma               | double | 1-sigma residual (arcsec)                                                    |
| 11 | start_date          | date   | Date of first observation used in orbit computation (DD/MM/YYYY)            |
| 12 | end_date            | date   | Date of last observation used in orbit computation (DD/MM/YYYY)             |
| 13 | px                  | double | x component of the EQJ2000 heliocentric position vector (au)                |
| 14 | py                  | double | y component of the EQJ2000 heliocentric position vector (au)                |
| 15 | pz                  | double | z component of the EQJ2000 heliocentric position vector (au)                |
| 16 | vx                  | double | x component of the EQJ2000 heliocentric velocity vector (au/d)              |
| 17 | vy                  | double | y component of the EQJ2000 heliocentric velocity vector (au/d)              |
| 18 | vz                  | double | z component of the EQJ2000 heliocentric velocity vector (au/d)              |
| 19 | fng_A1              | double | Radial non-gravitational acceleration (heliocentric EQJ2000)               |
| 20 | fng_A2              | double | Tangential non-gravitational acceleration (heliocentric EQJ2000)            |
| 21 | fng_A3              | double | Normal non-gravitational acceleration (heliocentric EQJ2000)                |
| 22 | tau                 | double | Date of perihelion passage (JD)                                             |
| 23 | perihelion_distance | double | Perihelion distance (au)                                                    |
| 24 | eccentricity        | double | Eccentricity                                                                |
| 25 | perihelion_argument | double | Argument of perihelion (deg) (J2000.0)                                       |
| 26 | node_longitude      | double | Longitude of the ascending node (deg) (J2000.0)                              |
| 27 | inclination         | double | Inclination to ecliptic (deg) (J2000.0)                                     |
| 28 | mag_H1              | double | Constant term of magnitude to compute the total magnitude                   |
| 29 | mag_R1              | double | Coefficient of log(r) to compute the total magnitude                        |
| 30 | mag_D1              | double | Coefficient of log(Delta) to compute the total magnitude                     |
| 31 | mag_H2              | double | Constant term of magnitude to compute the nuclear magnitude                 |
| 32 | mag_R2              | double | Coefficient of log(r) to compute the nuclear magnitude                      |
| 33 | mag_D2              | double | Coefficient of log(Delta) to compute the nuclear magnitude                  |
| 34 | selection           | int    | Selection flag (Section 4)                                                  |
| 35 | iddataset           | int    | Bibliographic unique reference                                              |

Fields follow the original COMETPRO data (Rocher & Cavelier, 1996).
Table A.5: Description of the fields in the collection **density** of the dataCloud.

| #   | Field             | Type    | Description                                                                 |
|-----|-------------------|---------|-----------------------------------------------------------------------------|
| 1   | num               | int     | SSO IAU Number                                                              |
| 2   | name              | varchar | SSO name                                                                    |
| 3   | density           | double  | Density in kg·m$^{-3}$                                                      |
| 4   | err_density_up    | double  | Upper uncertainty on the density (kg·m$^{-3}$)                               |
| 5   | err_density_down  | double  | Lower uncertainty on the density (kg·m$^{-3}$)                               |
| 6   | method            | varchar | Description of the method (Table B.1)                                       |
| 7   | selection         | int     | Selection flag (Section 4)                                                  |
| 8   | iddataset         | int     | Bibliographic unique reference                                              |

Table A.6: Description of the fields in the collection **diamalbedo** of the dataCloud.

| #   | Field            | Type    | Description                                                                 |
|-----|------------------|---------|-----------------------------------------------------------------------------|
| 1   | num              | int     | SSO IAU number                                                              |
| 2   | name             | varchar | SSO name                                                                    |
| 3   | diameter         | double  | Diameter in km                                                              |
| 4   | err_diameter_up  | double  | Upper uncertainty on the diameter (km)                                       |
| 5   | err_diameter_down| double  | Lower uncertainty on the diameter (km)                                       |
| 6   | albedo           | double  | Geometric visual albedo                                                     |
| 7   | err_albedo_up    | double  | Upper uncertainty on the albedo                                             |
| 8   | err_albedo_down  | double  | Lower uncertainty on the albedo                                             |
| 9   | beaming          | double  | Beaming parameter (Harris & Davies, 1999)                                   |
| 10  | err_beaming      | double  | Uncertainty on the beaming parameter                                         |
| 11  | emissivity       | double  | Emissivity (Harris & Davies, 1999)                                         |
| 12  | err_emissivity   | double  | Uncertainty on the emissivity                                               |
| 13  | selection        | int     | Selection flag (Section 4)                                                  |
| 14  | method           | varchar | Description of the method (Table B.1)                                       |
| 15  | iddataset        | int     | Bibliographic unique reference                                              |

Table A.7: Description of the fields in the collection **family** of the dataCloud.

| #   | Field            | Type    | Description                                                                 |
|-----|------------------|---------|-----------------------------------------------------------------------------|
| 1   | num              | int     | SSO IAU Number                                                              |
| 2   | name             | varchar | SSO name                                                                    |
| 3   | family_status    | varchar | SSO status: Core, Halo, Diffuse Halo                                        |
| 4   | family_num       | int     | IAU Number of the family (if named after an asteroid)                      |
| 5   | family_name      | varchar | Name of the family                                                          |
| 6   | selection        | int     | Selection flag (Section 4)                                                  |
| 7   | method           | varchar | Description of the method (Table B.1)                                       |
| 8   | iddataset        | int     | Bibliographic unique reference                                              |

Table A.8: Description of the fields in the collection **masses** of the dataCloud.

| #   | Field            | Type    | Description                                                                 |
|-----|------------------|---------|-----------------------------------------------------------------------------|
| 1   | num              | int     | SSO IAU Number                                                              |
| 2   | name             | varchar | SSO name                                                                    |
| 3   | mass             | double  | Mass in kg                                                                  |
| 4   | err_mass_up      | double  | Upper uncertainty on the mass (kg)                                          |
| 5   | err_mass_down    | double  | Lower uncertainty on the mass (kg)                                          |
Table A.8: continued.

| #  | Field    | Type     | Description                                                                 |
|----|----------|----------|------------------------------------------------------------------------------|
| 6  | method   | varchar  | Description of the method (Table B.1)                                       |
| 7  | selection| int      | Selection flag (Section 4)                                                   |
| 8  | method   | varchar  | Description of the method (Table B.1)                                       |
| 9  | iddataset| int      | Bibliographic unique reference                                               |

Table A.9: Description of the fields in the collection `mpcatobs` of the *dataCloud*.

| #  | Field           | Type    | Description                                                                 |
|----|-----------------|---------|------------------------------------------------------------------------------|
| 1  | type            | varchar | Type of SSO (asteroid, comet)                                                |
| 2  | num             | varchar | SSO number                                                                   |
| 3  | packed_name     | varchar | SSO packed name                                                              |
| 4  | name            | varchar | SSO name                                                                     |
| 5  | orbit_type      | varchar | Type of orbit (for comets)                                                   |
| 6  | discovery       | varchar | Discovery asterisk                                                           |
| 7  | note1           | varchar | See MPC Web site                                                            |
| 8  | note2           | varchar | See MPC Web site                                                            |
| 9  | date_obs        | datetime| Date of observation (ISO)                                                    |
| 10 | jd_obs          | double  | Date of observation (JD)                                                     |
| 11 | ra_obs          | double  | Observed right ascension (deg) (EQJ2000.0)                                   |
| 12 | dec_obs         | double  | Observed declination (deg) (EQJ2000.0)                                       |
| 13 | mag             | double  | Observed magnitude (mag)                                                     |
| 14 | filter          | varchar | Magnitude band                                                              |
| 15 | astrocata_name  | varchar | Astrometric reference catalog used to determine the position                 |
| 16 | astrocata_vizname| varchar | VizieR table base-name of the astrometric reference catalog                  |
| 17 | mpc_ref         | varchar | Permanent references to the MPCs, MPSs, or other journals                     |
| 18 | iau_code        | varchar | IAU observatory code                                                         |
| 19 | obs_long        | double  | Geographic longitude of observing site (deg)                                 |
| 20 | obs_lat         | double  | Geographic latitude of observing site (deg)                                  |
| 21 | obs_alt         | double  | Altitude of observing site (m)                                               |
| 22 | vgs_x           | double  | x component of spacecraft geocentric position vector (au) (EQJ2000.0)        |
| 23 | vgs_y           | double  | y component of spacecraft geocentric position vector (au) (EQJ2000.0)        |
| 24 | vgs_z           | double  | z component of spacecraft geocentric position vector (au) (EQJ2000.0)        |
| 25 | iddataset       | int     | Bibliographic unique reference                                               |

MPC Web site: [https://minorplanetcenter.net/iau/info/OpticalObs.html](https://minorplanetcenter.net/iau/info/OpticalObs.html)

Table A.10: Description of the fields in the collection `mpcorb` of the *dataCloud*.

| #  | Field               | Type    | Description                                                                 |
|----|---------------------|---------|------------------------------------------------------------------------------|
| 1  | packed_name         | varchar | Packed number or name of the SSO                                             |
| 2  | num                 | int     | SSO IAU Number                                                              |
| 3  | name                | varchar | SSO name                                                                     |
| 4  | H                   | double  | Absolute magnitude (mag)                                                     |
| 5  | G                   | double  | Slope parameter (Bowell et al., 1989)                                       |
| 6  | ref_date            | datetime| Reference epoch TT (ISO)                                                     |
| 7  | mean_anomaly        | double  | Mean anomaly (deg)                                                           |
| 8  | perihelion_argument | double  | Argument of perihelion (deg) in ECJ2000.0                                   |
| 9  | node_longitude      | double  | Longitude of ascending node (deg) ECJ2000.0                                  |
| 10 | inclination         | double  | Inclination (deg) in ECJ2000.0                                              |
| 11 | eccentricity        | double  | Eccentricity                                                                 |
### Table A.10: continued.

| #  | Field                | Type    | Description                                |
|----|----------------------|---------|--------------------------------------------|
| 12 | mean_motion          | double  | Mean motion (deg/d)                         |
| 13 | semi_major_axis      | double  | Semi-major axis (au)                        |
| 14 | U                    | varchar | Uncertainty parameter                      |
| 15 | reference            | varchar | Orbit reference                            |
| 16 | number_observation   | int     | Number of observations used to compute the orbit |
| 17 | number_opposition    | int     | Number of oppositions                      |
| 18 | start_obs            | int     | Year of the first observation              |
| 19 | end_obs              | int     | Year of the last observation               |
| 20 | orbital_arc          | double  | Orbit arc length (d)                       |
| 21 | rms                  | double  | Root-mean square residuals of the fit (arcsec) |
| 22 | coarse_indic         | varchar | Coarse indicator of perturbers             |
| 23 | precise_indic        | varchar | Precise indicator of perturbers            |
| 24 | orbit_computer       | varchar | Orbit computer                             |
| 25 | orbit_type           | varchar | 4-hexdigit flags describing the orbit      |
| 26 | last_obs             | double  | Date of last observation included in orbit solution (YYYYMMDD) |
| 27 | jd_osc               | double  | JD of the epoch of osculation              |
| 28 | px                   | double  | x component of heliocentric position vector (au, EQJ2000) |
| 29 | py                   | double  | y component of heliocentric position vector (au, EQJ2000) |
| 30 | pz                   | double  | z component of heliocentric position vector (au, EQJ2000) |
| 31 | vx                   | double  | x component of heliocentric velocity vector (au/d, EQJ2000) |
| 32 | vy                   | double  | y component of heliocentric velocity vector (au/d, EQJ2000) |
| 33 | vz                   | double  | z component of heliocentric velocity vector (au/d, EQJ2000) |
| 34 | orbital_period       | double  | Orbital period (d)                         |
| 35 | iddataset            | int     | Bibliographic unique reference            |

Fields follows the original MPCORB data, see the online documentation [https://www.minorplanetcenter.net/iau/info/MPOrbitFormat.html](https://www.minorplanetcenter.net/iau/info/MPOrbitFormat.html).

### Table A.11: Description of the fields in the collection pairs of the dataCloud.

| #  | Field      | Type | Description                                      |
|----|------------|------|--------------------------------------------------|
| 1  | num        | int  | First member IAU Number                          |
| 2  | name       | varchar | First member name                               |
| 3  | sibling_num| int  | Second member IAU Number                         |
| 4  | sibling_name| varchar | Second member name                              |
| 5  | distance   | double | Orbital distance (m/s)                          |
| 6  | age        | double | Estimated age of the pair (kyr)                  |
| 7  | err_age_up | double | Upper uncertainty on the age (kyr)               |
| 8  | err_age_down | double | Lower uncertainty on the age (kyr)               |
| 9  | selection  | int  | Selection flag (Section 4)                       |
| 10 | method     | varchar | Description of the method (Table B.1)           |
| 11 | iddataset  | int  | Bibliographic unique reference                   |

### Table A.12: Description of the fields in the collection phase_function of the dataCloud.

| #  | Field  | Type  | Description                                      |
|----|--------|-------|--------------------------------------------------|
| 1  | num    | int   | SSO IAU Number                                   |
| 2  | name   | varchar | SSO name                                         |
| 3  | H      | double | Absolute magnitude                               |
| 4  | G1     | double | Phase parameter $G_1$ (Muinonen et al., 2010)    |
Table A.12: continued.

| #  | Field            | Type   | Description                                                                 |
|----|------------------|--------|-----------------------------------------------------------------------------|
| 5  | G2               | double | Phase parameter $G_2$ (Muinonen et al., 2010)                                |
| 6  | err_H_down       | double | Lower uncertainty on absolute magnitude                                     |
| 7  | err_H_up         | double | Upper uncertainty on absolute magnitude                                     |
| 8  | err_G1_down      | double | Lower uncertainty on $G_1$ phase parameter                                  |
| 9  | err_G1_up        | double | Upper uncertainty on $G_1$ phase parameter                                  |
| 10 | err_G2_down      | double | Lower uncertainty on $G_2$ phase parameter                                  |
| 11 | err_G2_up        | double | Upper uncertainty on $G_2$ phase parameter                                  |
| 12 | N                | double | Number of observations used to derive $\left( H, G_1, G_2 \right)$           |
| 13 | phase_min        | double | Minimum phase angle (°)                                                    |
| 14 | phase_max        | double | Maximum phase angle (°)                                                    |
| 15 | rms              | double | Root mean-square of the fit (mag)                                          |
| 16 | facility         | varchar| Source of observations (telescope, survey)                                  |
| 17 | name_filter      | varchar| Name of the filter                                                         |
| 18 | id_filter        | varchar| Filter unique identifier (SVO filter service, Rodrigo et al., 2012)          |
| 19 | method           | varchar| Description of the method (Table B.1)                                      |
| 20 | selection        | int    | Selection flag (Section 4)                                                 |
| 21 | iddataset        | int    | Bibliographic unique reference                                             |

Table A.13: Description of the fields in the collection *proper_elements* of the *dataCloud*.

| #  | Field                            | Type   | Description                                                                 |
|----|----------------------------------|--------|-----------------------------------------------------------------------------|
| 1  | num                             | int    | SSO IAU Number                                                              |
| 2  | name                            | varchar| SSO name                                                                    |
| 3  | H                               | double | Absolute magnitude                                                          |
| 4  | proper_semi_major_axis          | double | Proper semi-major axis (au)                                                 |
| 5  | err_proper_semi_major_axis      | double | Uncertainty on proper semi-major axis (au)                                   |
| 6  | proper_eccentricity             | double | Proper eccentricity                                                          |
| 7  | err_proper_eccentricity         | double | Uncertainty on proper eccentricity                                           |
| 8  | proper_sine_inclination         | double | Sine of proper inclination                                                  |
| 9  | err_proper_sine_inclination     | double | Uncertainty on sine of proper inclination                                    |
| 10 | proper_inclination              | double | Proper inclination (°)                                                      |
| 11 | err_proper_inclination          | double | Uncertainty on proper inclination (°)                                        |
| 12 | proper_frequency_mean_motion    | double | Proper frequency of mean motion (°/yr)                                      |
| 13 | err_proper_frequency_mean_motion| double | Uncertainty on proper frequency of mean motion (°/yr)                       |
| 14 | proper_frequency_perihelion_longitude| double | Proper frequency of perihelion longitude (arcsec/yr)                      |
| 15 | err_proper_frequency_perihelion_longitude| double | Uncertainty on proper frequency of perihelion longitude (arcsec/yr)        |
| 16 | proper_frequency_nodal_longitude | double | Proper frequency of nodal longitude (arcsec/yr)                             |
| 17 | err_proper_frequency_nodal_longitude | double | Uncertainty on proper frequency of nodal longitude (arcsec/yr)            |
| 18 | lyapunov_time                   | double | Timescale of chaoticity (yr)                                                |
| 19 | integration_time                | double | Length of integration (Myr)                                                 |
| 20 | identfrom                      | varchar| Name of the SSO in the imported data                                        |
| 21 | iddataset                      | int    | Bibliographic unique reference                                              |
Table A.14: Description of the fields in the collection *spin* of the *dataCloud*.

| #  | Field     | Type   | Description                                                                 |
|----|-----------|--------|-----------------------------------------------------------------------------|
| 1  | num       | int    | SSO IAU Number                                                              |
| 2  | name      | varchar| SSO name                                                                    |
| 3  | model_name| varchar| Name of the model                                                           |
| 4  | t0        | double | Reference epoch for spin coordinates (JD)                                   |
| 5  | W0        | double | Rotation phase at t0 ($^\circ$, Archinal et al., 2018)                      |
| 6  | Wp        | double | Rotation velocity ($^\circ$/d, Archinal et al., 2018)                       |
| 7  | RA0       | double | EQJ2000 right ascension of the spin axis ($^\circ$)                         |
| 8  | DEC0      | double | EQJ2000 declination of the spin axis ($^\circ$)                             |
| 9  | err_RA0   | double | Uncertainty on the right ascension ($^\circ$)                               |
| 10 | err_DEC0  | double | Uncertainty on the declination ($^\circ$)                                   |
| 11 | period    | double | Rotation period (h)                                                         |
| 12 | err_period| double | Uncertainty on rotation period (h)                                           |
| 13 | period_flag| double | Rotation period quality code (Warner et al., 2021)                          |
| 14 | period_type| varchar| Sidereal or synodic                                                         |
| 15 | long      | double | ECJ2000 longitude of the spin axis ($^\circ$)                               |
| 16 | lat       | double | ECJ2000 latitude of the spin axis ($^\circ$)                                |
| 17 | err_long  | double | Uncertainty on the longitude ($^\circ$)                                     |
| 18 | err_lat   | double | Uncertainty on the latitude ($^\circ$)                                      |
| 19 | selection | int    | Selection flag (Section 4)                                                  |
| 20 | method    | varchar| Description of the method (Table B.1)                                      |
| 21 | iddataset | int    | Bibliographic unique reference                                              |

Table A.15: Description of the fields in the collection *taxonomy* of the *dataCloud*.

| #  | Field     | Type   | Description                                                                 |
|----|-----------|--------|-----------------------------------------------------------------------------|
| 1  | num       | int    | SSO IAU Number                                                              |
| 2  | name      | varchar| SSO name                                                                    |
| 3  | scheme    | varchar| Taxonomic scheme (e.g., Tholen, Bus, DeMeo, Mahlke)                         |
| 4  | class     | varchar| Taxonomic class                                                             |
| 5  | complex   | varchar| Taxonomic complex (Table C.8)                                              |
| 6  | selection | int    | Selection flag (Section 4)                                                  |
| 7  | method    | varchar| Description of the method (Table B.1)                                      |
| 8  | waverange | varchar| Waverange used in taxonomy (VIS, NIR, VISNIR)                               |
| 9  | iddataset | int    | Bibliographic unique reference                                              |

Table A.16: Description of the fields in the collection *thermal_properties* of the *dataCloud*.

| #  | Field     | Type   | Description                                                                 |
|----|-----------|--------|-----------------------------------------------------------------------------|
| 1  | num       | int    | SSO IAU Number                                                              |
| 2  | name      | varchar| SSO name                                                                    |
| 3  | TI        | double | Thermal Inertia ($J.s^{-1/2}K^{-1/2}m^{-2}$)                                |
| 4  | err_TI_up | double | Upper uncertainty on the thermal inertia                                    |
| 5  | err_TI_down| double | Lower uncertainty on the thermal inertia                                    |
| 6  | dsun      | double | Heliocentric distance at the time of measurements (au)                      |
| 7  | selection | int    | Selection flag (Section 4)                                                  |
| 8  | method    | varchar| Description of the method (Table B.1)                                      |
| 9  | iddataset | int    | Bibliographic unique reference                                              |
Table A.17: Description of the fields in the collection yarkovsky of the dataCloud.

| #  | Field     | Type   | Description                                           |
|----|-----------|--------|-------------------------------------------------------|
| 1  | num       | int    | SSO IAU Number                                        |
| 2  | name      | varchar| SSO name                                              |
| 3  | A2        | double | Radial acceleration ($10^{-15}$ au/$d^2$)             |
| 4  | err_A2    | double | Uncertainty on radial acceleration ($10^{-15}$ au/$d^2$) |
| 5  | dadt      | double | Semi-major drift ($10^{-4}$ au/Myr)                   |
| 6  | err_dadt  | varchar| Uncertainty on semi-major drift ($10^{-4}$ au/Myr)    |
| 7  | snr       | float  | Signal-to-noise ratio                                 |
| 8  | S         | float  | Sensitivity parameter (Nugent et al., 2012)           |
| 9  | selection | int    | Selection flag (Section 4)                            |
| 10 | method    | varchar| Description of the method (Table B.1)                |
| 11 | iddataset | int    | Bibliographic unique reference                       |
### Appendix B: Description of all the methods

Table B.1: Methods included in SsODNet.

| Method  | Name                                  | Description                                                                                       | Reference                      |
|---------|----------------------------------------|---------------------------------------------------------------------------------------------------|--------------------------------|
| SPACE   | Rendez-vous with a spacecraft          | The results are based on data which had an encounter (flyby or orbit) with the target           | Belton et al. (1992)           |
| STM     | Standard Thermal Model                 | Diameter and albedo derived by fitting mid-infrared data with a simple thermal model of non-rotating spheres | Lebofsky et al. (1986)         |
| NEATM   | Near-Earth Asteroid Thermal Model      | Diameter, albedo, beaming derived by fitting mid-infrared data with a simple thermal model        | Harris & Davies (1999)         |
| TPM     | ThermoPhysical Model                   | Diameter, albedo, thermal inertia derived by fitting mid-infrared data with a thermal model taking into account the spin, shape of the target | Lagerros (1996)                |
| PhaseFunction | Albedo determined from the phase function | Albedo determined from the phase function                                                    | Belskaya & Shevchenko (2000) |
| LC      | Lightcurve                             | Rotation period determined from optical lightcurves                                             | Zessewitsch (1932)            |
| Comet-Break | Mass from break-up         | Mass estimated from the break-up of the comet                                                   | Solem (1994)                  |
| FRM     | Fast Rotating Model                    | Diameter and albedo derived by fitting mid-infrared data with a simple thermal model of rapidly non-rotating spheres | Lebofsky & Spencer (1989)     |
| NESTM   | Night Emission Simulated Thermal Model | Diameter, albedo, beaming derived by fitting mid-infrared data with an adapted NEATM            | Wolters & Green (2009)        |
| Speckle | Triaxial ellipsoid from speckle interferometry | 3D shape modeled as tri-axial ellipsoid using speckle interferometry | Drummond et al. (1985)        |
| Interferometry | Optical and Infrared Interferometry | Diameter derived from interferometric visibilities in the optical or infrared | Delbo et al. (2009)           |
| Occ     | Stellar Occultation                    | Apparent size measured during a stellar occultation                                             | Dunham & Mallen (1979)        |
| IM      | Apparent shape from direct imaging     | Apparent size/shape measured on disk-resolved images                                             | Marchis et al. (2006)         |
| IM-PSF  | Diameter from PSF deviation            | Estimate of diameter from the deviation of the PSF compared with a star                         | Brown & Trujillo (2004)       |
| TE-IM   | Triaxial ellipsoid from disk-resolved imaging | 3D shape modeled as tri-axial ellipsoid using disk-resolved images | Drummond (2000)               |
| TE-Occ  | Triaxial ellipsoid from stellar occultation | 3D shape modeled as tri-axial ellipsoid using stellar occultations | Drummond & Cocke (1989)      |
| ADAM    | All-Data Asteroid Model                | 3D shape model obtained from a combined use of stellar occultations, optical lightcurves, disk-resolved images, interferometric fringes | Viikinkoski et al. (2015)    |
| Method       | Name                                      | Description                                                                                           | Reference               |
|--------------|-------------------------------------------|-------------------------------------------------------------------------------------------------------|-------------------------|
| KOALA        | Knitted Occultation, Adaptive-optics, and Lightcurves Analysis | The results are obtained from the combined use of stellar occultation, optical lightcurves, and disk-resolved images | Carry et al. (2010)     |
| Radar        | Radar shape modeling                      | 3D shape model based on radar Delay-Doppler data                                                     | Hudson & Ostro (1994)   |
| Radar-LC     | Combined radar and lightcurve shape modeling | 3D shape model based on radar Delay-Doppler and optical lightcurve data                               | Hudson et al. (1997)    |
| SAGE         | Shaping Asteroids with Genetic Evolution   | 3D shape model based on lightcurves, found by genetic evolution                                      | Bartczak & Dudziński (2018) |
| Polarimetry  | Albedo determined from polarimetry         | Albedo determined from polarimetry                                                                  | Cellino et al. (1999)   |
| A-M          | Amplitude-Magnitude                        | Determination of the spin axis from the amplitude of lightcurves                                     | Zappala et al. (1983)   |
| TE           | Triaxial ellipsoid from lightcurves        | Determination of the spin axis, modeling the lightcurves with a triaxial ellipsoid                  | Hanuš et al. (2021)     |
| LCI          | Lightcurve Inversion                       | Spin and convex 3-D shape determined from optical lightcurves                                        | Kaasalainen & Torppa (2001) |
| LC+Occ       | Scaling of Lightcurve Inversion Model with Stellar Occultations | 3D shape model from lightcurve inversion scaled using stellar occultation(s)                      |Ďurech et al. (2011)     |
| LC+IM        | Scaling of Lightcurve Inversion Model with Direct Imaging | 3D shape model from lightcurve inversion scaled using disk-resolved image(s)                      | Hanuš et al. (2013b)    |
| LC+TPM       | Scaling of Lightcurve Inversion Model with ThermoPhysical Model | 3D shape model from lightcurve inversion scaled using a thermophysical model on mid-infrared data | Hanuš et al. (2015)     |
| LC-TPM       | Combined lightcurve inversion and ThermoPhysical modeling | 3D shape modeling from simultaneous lightcurve inversion and thermophysical model of mid-infrared data |Ďurech et al. (2017)     |
| EPHEM        | Mass from ephemerides                      | The mass is determined from general ephemerides of the Solar System                                 | Baer & Chesley (2008)   |
| DEFLECT      | Mass from close encounter deflection       | The mass is determined from the orbital deflection of smaller asteroids                              | Standish & Hellings (1989) |
| Bin-IM       | Mass from optical imaging a binary system  | Mass from a binary system imaged in the optical                                                    | Merline et al. (1999)   |
| Bin-Radar    | Mass from radar observations of a binary system | Mass from a binary system observed by radar echoes                                                 | Ostro et al. (2006)     |
| Bin-PheMu    | Mass from mutual phenomena in a binary system | Mass from a binary system from the timings/shape of mutual event from lightcurves                  | Pravec et al. (2000)    |
| Bin-Genoid   | Orbit and mass from a multiple asteroidal system using Genoid algorithm | Orbital elements and mass determination from a multiple asteroidal system with Genoid             | Vachier et al. (2012) |
| Yarkovsky    | Mass from Yarkovsky drift                 | Determination of the mass from the measured Yarkovsky drift                                         | Chesley et al. (2014)   |
| Method          | Name                        | Description                                                                 | Reference                  |
|-----------------|-----------------------------|-----------------------------------------------------------------------------|----------------------------|
| Comet-NGF       | Mass from non-gravitational forces | Mass estimated from the non-gravitational acceleration                      | Davidsson et al. (2007)    |
| Spec            | Reflectance spectroscopy     | Reflectance spectroscopy                                                    | McCord et al. (1970)       |
| Phot            | Multi-filter photometry      | Multi-band photometry                                                       | DeMeo & Carry (2013)       |
| Astrometry(O)   | Yarkovsky drift from optical astrometry | Determination of the semi-major drift due to Yarkovsky using astrometry from optical observations | Chesley et al. (2003)     |
| Astrometry(O+R) | Yarkovsky drift from optical astrometry and radar delays | Determination of the semi-major drift due to Yarkovsky using astrometry from optical observations and radar delays | Chesley et al. (2003)     |
| Family_age      | Yarkovsky drift from family age | Determination of the semi-major drift due to Yarkovsky using the age of the dynamical family | Carruba et al. (2017)      |
| HCM             | Hierarchical Clustering Method | Determination of family membership by hierarchical clustering of proper elements | Zappala et al. (1990)      |
| V-Shape         | Yarkovsky V-shape identification of asteroid families | Determination of family membership by identification of Yarkovsky print in (semi-major axis, 1/diameter) plane | Bolin et al. (2017)        |
| abs             | Colors derived from absolute magnitudes | Colors computed from the absolute magnitudes in the two filters | Mahlke et al. (2021)       |
| lc_cor          | Colors derived from apparent magnitudes corrected for lightcurve | Colors computed from the apparent magnitudes, corrected for short-term variability introduced by lightcurve | Erasmus et al. (2019)      |
| app             | Colors derived from apparent magnitudes | Colors computed from the apparent magnitudes | Sykes et al. (2000)        |
| Yarkovsky_drift | Thermal inertia derived from Yarkovsky drift | Determination of the thermal inertia based on the measured strength of the Yarkovsky effect | Fenucci et al. (2021)      |
| serendipitous   | Phase curve from serendipitous observations | Determination of the parameters of the phase function from serendipitous observations (from surveys) | Oszkiewicz et al. (2011)   |
| targeted        | Phase curve from targeted observations | Determination of the parameters of the phase function from targeted observations (generally reduction to lightcurve maxima) | Gehrels (1956)             |
Appendix C: Method lists for best-estimate determination

Table C.1: Ranking of methods for diameter estimates (diamalbedo).

| Order | Methods                                      |
|-------|----------------------------------------------|
| 1     | SPACE                                        |
| 2     | ADAM, KOALA, SAGE, Radar                    |
| 3     | LC+Occ, LC+IM, LC+TPM, TPM, TE-IM, TE-Occ   |
| 4     | IM, Occ, IM-PSF, Interferometry             |
| 5     | NEATM, NESTM                                |
| 6     | STM, FRM                                     |
| 7     | Polarimetry                                  |

The order favors direct measurements first, then estimates based on 3D shape models, followed by direct measurements limited to a single geometry. Last are indirect estimates from thermal model of spheres.

Table C.2: Selection order for albedo determinations (diamalbedo).

| Order | Methods   |
|-------|-----------|
| 1     | SPACE     |
| 2     | Polarimetry|

Table C.3: Selection order for mass determinations (masses).

| Order | Methods                                      |
|-------|----------------------------------------------|
| 1     | SPACE                                        |
| 2     | Bin-Genoid                                   |
| 3     | Bin-IM, Bin-Radar, Bin-PheMu                 |
| 4     | Deflect, Ephem                               |
| 5     | Yarkovsky                                    |

The order favors spacecraft encounters, followed by binary systems. Last are estimates based on long-distance gravitational interactions and Yarkovsky drift.

Table C.4: Ranking of methods for spin properties (spin).

| Order | Methods                                      |
|-------|----------------------------------------------|
| 1     | SPACE                                        |
| 2     | ADAM, KOALA, SAGE, Radar, Radar-LC           |
| 3     | LC+TPM, LC-TPM, LC+IM, LC+Occ               |
| 4     | LCI                                          |
| 5     | LC, A-M, Bin-IM, TE, TE-IM, TE-Occ, Speckle |

The order favors solutions from spacecraft encounters, followed by 3D shape modeling, ranked from modeling including direct measurement to scaling of 3D convex models, to convex model of arbitrary size. Simple ellipsoids follow, and finally periods from light-curves.

Table C.5: Selection order for colors (colors).

| Order | Methods             |
|-------|---------------------|
| 1     | Absolute            |
| 2     | Light-curve corrected|
| 3     | Apparent            |

The order favors absolute magnitude, over light-curve corrected, over apparent magnitude.
Table C.6: Ranking of methods for thermal properties (thermal_properties).

| Order | Methods                  |
|-------|--------------------------|
| 1     | SPACE                    |
| 2     | LCI-TPM, LCI+TPM         |
| 3     | TPM                      |
| 4     | Yarkovsky_drift          |

The order favors estimates from space mission encounters, then thermophysical models based on 3D shapes. Last are estimates from thermophysical models based on limited shape/spin information.

Table C.7: Selection order for Yarkovsky drift determinations (yarkovsky).

| Order | Methods                   |
|-------|---------------------------|
| 1     | Astrometry(O+R)           |
| 2     | Astrometry(O)             |
| 3     | Family_age                |

The order favors solutions using a combination of optical and radar observations over optical-only data sets. Last are estimates based on family ages.

Table C.8: Class-complex connections for taxonomy.

| Complex | Reference                          | Classes                                                                 |
|---------|------------------------------------|------------------------------------------------------------------------|
| A       | Veeder et al. (1983)               | A                                                                      |
| B       | Tholen (1984)                      | B                                                                      |
| C       | Chapman et al. (1975)              | C, Cb, CF, CFB, Cg, CG, Cgx, F, FC, G, GC                              |
| Ch      | Bus & Binzel (2002)                | Caa, Cgh, Ch                                                           |
| D       | Gradie & Tedesco (1982)            | D                                                                      |
| E       | Zellner & Gradie (1976)            | E                                                                      |
| K       | Tedesco et al. (1989)              | K                                                                      |
| L       | Bell et al. (1988)                 | L, Ld                                                                 |
| M       | Zellner & Gradie (1976)            | M                                                                      |
| D       | Binzel et al. (1993)               | O                                                                      |
| P       | Gradie & Tedesco (1982)            | DP, P, PD                                                              |
| Q       | Tholen (1984)                      | Q, Q0, Qw                                                              |
| R       | Bowell et al. (1978)               | R                                                                      |
| S       | Chapman et al. (1975)              | S, SA, Sa, Sk, Sl, SO, Sq, SQ, Sqw, Sr, SR, Srw, SV, Sv, Svw, Sw       |
| T       | Zellner & Bowell (1977)            | T                                                                      |
| V       | McCord et al. (1970)               | J, V, Vw                                                              |
| X       | Tholen (1984)                      | EM, X, Xc, Xe, Xk, Xn, Xt                                             |
| Z       | Mueller et al. (1992)              | Z                                                                      |
| U       | Ad, AQ, AS, AU, AV, BC, BCF, BCU, BFC, BFU, BFX, Ek, BU, CB, CBU, CD, CDX, CFU, CFXU, CGSU, CGTP, CGU, CL, CO, CP, CFP, CPU, CQ, CS, CSGU, CSU, CTGU, CU, CX, CF, DCX, DL, Ds, DS, DSU, DT, DU, DX, DXCU, EU, EBCU, FCB, FCU, FCFX, FP, FU, FX, FXU, GS, GU, I, K1, LA, LQ, LS, MU, O, PC, PCD, PDC, PF, PU, QRS, QSV, QU, QV, SC, SCTU, SD, SBU, SG, SBU, ST, STD, STGD, STU, SU, SX, TCG, TD, TDG, TDS, TS, TSD, TX, XB, XC, XCU, XD, XDC, XF, XFC, XFCU, XFU, XL, XS, XSC, XSCU, XT, XU |

The references indicate where the class/complex archetype was labeled as such for the first time.