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Implementing a New Backend for SB9 Catalogue of Spectroscopic Binary Orbits

Design and migration to a scalable and interoperable astronomical database

Mémoire présenté en vue de l'obtention du diplôme
de Master de spécialisation en science des données, Big Data

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Abstract

The 9th Catalogue of Spectroscopic Binary Orbits (SB9) has long served as a reference for binary star research, compiling orbital solutions from decades of publications. However, its legacy infrastructure—based on flat text files and an outdated web interface—posed serious limitations in terms of accessibility, interoperability, and maintainability.

The project involved migrating the catalog into a relational SQL database with well-defined constraints, ensuring data consistency and enabling more powerful queries. The catalog was enriched using high-precision astrometric data from Gaia DR3 and other external sources, significantly improving the completeness and accuracy of astronomical objects position, movement and magnitude. A new web interface with backend logic was developed, featuring a flexible search engine, interactive orbital visualizations, and the ability to download measurements data.

To align with community standards, a standardized data query service was deployed, facilitating seamless integration with external tools and data extraction for analysis. The result is a catalog renamed SBX -The eXtended Catalog of Spectroscopic Binary Orbits- which opens new perspectives for community-driven extensions, enhances user interaction, and large-scale statistical studies of binary stars.

Motivations

Astronomers have long been driven by the need to understand the cosmos, beginning with the observation of visible celestial bodies and gradually expanding their focus to include the dynamic properties of stars, galaxies, and other astrophysical phenomena. The stars, in particular, offer a unique laboratory: by analyzing their light, motions, and interactions, we can infer properties of the universe, from stellar evolution to galactic structure and the presence of exoplanets.

In recent decades, the development of increasingly powerful observational instruments has transformed the scale and nature of data in astronomy. The Gaia space telescope, for instance, is mapping the positions, motions, and physical characteristics of over a billion stars with unprecedented precision. This leap in data volume has opened the door to entirely new scientific questions, but it also demands new infrastructure to manage, process, and share these massive datasets.

Historically, astronomers began by compiling star charts and catalogs manually. As observational methods improved, so did the complexity and size of these catalogs. Printed atlases gave way to digital databases, allowing for more efficient storage, cross-referencing, and statistical analyses. Projects such as the 9th Catalogue of Spectroscopic Binary Orbits (SB9) illustrate this progression—maintaining and updating such a specialized catalog now involves not only astrophysical expertise but also robust data engineering practices.

Astronomy stands out among the sciences for its long-standing engagement with information technology. As emphasized in the VOTable specification by the International Virtual Observatory Alliance (IVOA), "Astronomers have always been at the forefront of developments in information technology." (Bonnarel et al. (2025)) This trend has been reinforced by the Virtual Observatory movement, which promotes the adoption of scalable, interoperable data solutions not only to meet astronomy's needs, but to serve as a model for other disciplines as well.

The growing complexity of astronomical data calls for modern solutions. Interoperability, sustainability, and accessibility are no longer optional—they are essential. By developing a durable, queryable, and standards-compliant database system for SB9, this thesis contributes to the broader effort of ensuring that astronomical knowledge remains usable, shareable, and scientifically fertile in the era of big data.

Chapter 1

Introduction

1.1 Spectroscopic binary stars

A substantial fraction of stars in our galaxy are not isolated, but rather found in gravitationally bound binary (or multiple) systems. Among these, spectroscopic binaries are systems in which two (or more) stars orbit around a common center of mass and are detected through the analysis of their spectral lines rather than directly imaged. These systems are typically spatially unresolved by conventional telescopes, as their angular separation is too small to distinguish individual components.

Detection relies on the Doppler effect: the radial motion of each component induces periodic shifts in the observed spectral lines. When one star approaches and the other recedes, their respective absorption lines shift towards the blue and red ends of the spectrum. Monitoring these variations allows astronomers to infer the presence of a companion, even when the binary is spatially unresolved. Spectroscopic binaries are designated as SB1 or SB2 depending on whether one or both stellar components are spectroscopically visible.

While these represent just one category within the broader taxonomy of stellar systems—including visual binaries, eclipsing binaries, and astrometric binaries—they are particularly valuable because spectroscopy provides access to dynamical information such as orbital velocities and mass function for SB1, and mass-ratio for SB2. It is also worth noting that multiple-star systems, beyond binaries, are not uncommon and play a crucial role in the understanding of stellar formation and evolution.

1.2 Binary Star Parameters

The analysis of spectroscopic binary stars involves the determination of several physical and orbital parameters. First and foremost, the spatial location of the system is established through coordinates—right ascension and declination—along with the parallax, which yields the distance.

The dynamical behavior of the binary is encoded in radial velocity curves (see figure 1.1), which describe how the radial velocities of the components vary over time. These variations follow Keplerian motion, and can be modeled using the orbital elements. For each component, the radial velocity as a function of time is given by:

$$v_1(t) = V_0 + K_1\left[\cos(\nu(t) + \omega_1) + e\cos(\omega_1)\right] \tag{1.1}$$

$$v_2(t) = V_0 - K_2\left[\cos(\nu(t) + \omega_2) + e\cos(\omega_2)\right] \tag{1.2}$$

where:

- V_0 is the systemic velocity of the binary,
- K_1 and K_2 are the velocity semi-amplitudes of the primary and secondary components,
- ω_1 and ω_2 are the arguments of periastron (equal in value but 180° out of phase),
- e is the orbital eccentricity,
- $\nu(t)$ is the true anomaly as a function of time.

From the measured semi-amplitudes and orbital elements, one can derive physical quantities such as the projected semi-major axis:

$$a_1 \sin i = \frac{K_1 P (1-e^2)^{1/2}}{2\pi} \tag{1.3}$$

and the mass function:

$$f(m) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{P K_1^3 (1-e^2)^{3/2}}{2\pi G} \tag{1.4}$$

In double-lined systems (SB2), the mass ratio q is directly given by:

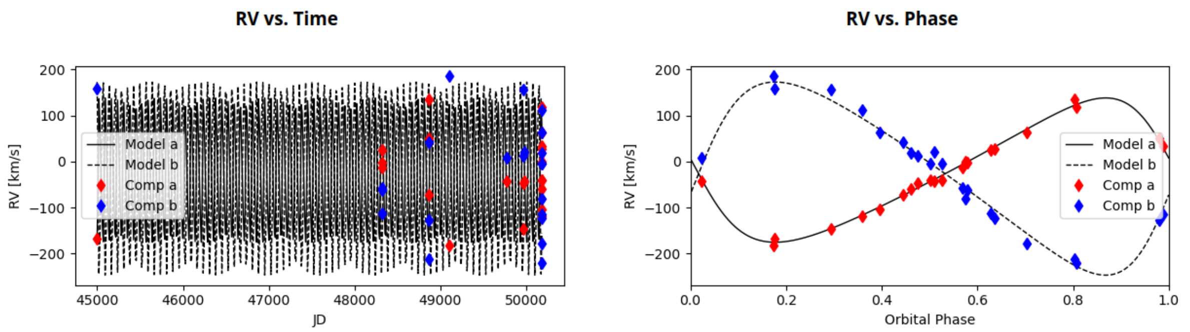

Figure 1.1: Radial Velocity curve of an SB2 binary star (HD 152218), measured velocities over time (Julian Date) on left, measured velocity refolded over orbital phase on right.

$$q = \frac{M_2}{M_1} = \frac{K_1}{K_2} \tag{1.5}$$

However, absolute masses can only be determined if the orbital inclination i is known. This is possible in specific configurations, such as eclipsing binaries (seen nearly edge-on) or systems for which astrometric measurements can resolve the motion of the components on the sky.

In resolved systems, additional parameters such as angular separation and position angle can be obtained via imaging or interferometry. Nevertheless, for the majority of spectroscopic binaries, the emphasis remains on radial velocity monitoring. The systematic collection and curation of these parameters in standardized catalogs remains a cornerstone of stellar astrophysics.

1.3 The 9th Catalogue of Spectroscopic Binary Orbits (SB9)

The 9th Catalogue of Spectroscopic Binary Orbits (SB9) Pourbaix et al. (2004) is the continuation of a long-standing effort to compile orbital elements of spectroscopic binaries. It was started at Lick Observatory Campbell and Curtis (1905) and extended manually through its eighth version (SB8) Batten et al. (1989), namely the last paper published edition.

SB9 marked the digitization of the catalog and kept on consolidating with new orbits to enable statistical studies, assist in selecting targets for follow-up observations, and give an overview of the progress made in spectroscopic binary research. Its latest release includes approximately 4000 systems and over 5000 orbital solutions.

It also contains numerous notes and bibliographic references, making it a widely used resource for comparative work on binary stars. However, the database is outdated in its format and infrastructure, and needs modernization to remain compatible with tools and datasets like those from ESA Gaia space mission Collaboration et al. (2016).

1.3.1 Data Storage

The SB9 catalog is maintained as a collection of plain-text files. Each table is stored in a separate file, using pipe-separated values as field delimiters. The various files contain each a table, already reflecting a relational database structure, with shared keys linking the different datasets. New data have mostly been extracted by contributors from publications and appended.

This approach, while simple, lacks the safeguards and structure of a formal database management system (DBMS, see Ramakrishnan and Gehrke (2003)), which has led to inconsistencies in data entry, deviations from the expected table formats, and the presence of errors and duplicate entries.

1.3.2 User Interface and Query System

The web interface is very basic in graphics, with the back-end logic implemented through a set of bash and CGI scripts (Common Gateway Interface, see Boutell and Robinson (2004)). These scripts handle form input, data parsing, and output generation in a minimal and rigid way, offering little flexibility or resilience. Users can query the catalog through a basic lookup form, but the interface lacks tolerance for typos, partial matches, or alternative naming conventions. Graphs of radial velocity curves are rendered using PostScript, a legacy graphics format.

1.3.3 Limitations

Although functional, the current SB9 setup poses clear limitations in terms of maintainability, scalability, and usability—emphasizing the need for a more robust, accessible, and standards-compliant infrastructure.

One major shortcoming is the lack of standardization across data fields. Unlike other modern astronomical databases, SB9 uses informal or legacy conventions for representing quantities such as radial velocities, spectral types, or bibliographic codes. For instance missing values are inconsistently encoded (e.g., using dashes), and there is no enforced schema to ensure uniformity. This complicates downstream data processing and prevents interoperability with other catalogs.

The existing interface only allows lookup of one system at a time, based on an exact match to an identifier from a limited set of catalog names. This rigidity makes the interface error-prone for end users and nearly unusable for batch queries or statistical analysis. An alternative is to download the entire catalog as an archive and manually parse the raw text files—an approach that is both cumbersome and fragile, especially when automated pipelines are required.

This lack of flexibility also creates challenges for external services. For instance, maintainers of Simbad database have indicated that incorporating SB9 updates is labor-intensive. Any change in table format or file structure necessitates corresponding modifications to their ingestion scripts, which increases maintenance burden and reduces update frequency.

Moreover, the lookup tool provides no tolerance for input errors: even minor deviations in naming conventions (e.g., extra spaces or inconsistent case) can cause the query to fail. There is no fuzzy matching, alias resolution, or support for advanced search criteria such as sky aperture.

This work aims to address these limitations by migrating SB9 into a queryable SQL database, exposing it through a Virtual Observatory-compliant TAP service, and redesigning the web interface to support flexible, user-friendly search and data exploration.

1.3.4 Key Astronomical Resources

This work relies on several foundational resources developed and maintained by the international astronomical community. Among the most central is the **Centre de Données astronomiques de Strasbourg** (CDS), which operates key services such as:

- **Simbad** — a reference database for astronomical objects, offering cross-identifications, basic data, and bibliography;
- **Sesame** — a name resolver that parses and standardizes object identifiers across catalogs;

- **VizieR** — a repository of more than 20,000 astronomical catalogs, including the SB9 catalog itself.

Another essential framework is the **International Virtual Observatory Alliance** (IVOA), which establishes and promotes interoperability standards for astronomical data services. Protocols such as TAP (Table Access Protocol) and data formats like VOTable ensure that resources can be accessed in a consistent and machine-readable manner across institutions.

A third cornerstone of this project is the **Gaia Archive**, which provides access to data collected by the European Space Agency's Gaia mission. In particular, Gaia Data Release 3 (DR3) (Vallenari et al. (2023)) serves as the primary source of updated astrometric parameters—such as position, proper motion, and parallax—for thousands of systems in SB9.

These resources collectively set guidelines for the modernization of the SB9 catalog.

Chapter 2

Database Migration

The following sections introduce substantial changes to the SB9 catalog. To reflect this evolution, the updated version has been renamed SBX —the eXtended Catalogue of Spectroscopic Binary Orbits. This new designation will be used throughout the remainder of this document for clarity.

2.1 Relational Database Generalities

Relational databases are a foundational technology in information systems, designed to store, manage, and retrieve structured data efficiently. First introduced by Codd (1970), this model organizes data into tables (called relations) composed of rows and columns, where each row represents a record and each column corresponds to an attribute. It generally is the preferred choice for datasets with clear structure and relationships, due to their support for consistency through schema enforcement.

Structured Query Language (SQL, see Molinaro (2004)) is the standard language used to interact with relational databases. It allows users to define schemas, insert and update records, retrieve data through queries, and manage access control. SQL is tightly bound to the relational model, enabling complex data manipulation and relational operations. It should be noted that the terms relational database and SQL database are commonly used interchangeably although the latest is only a general language defined to implement the theoretical concept of relational database.

The primary objects in a relational database are:

- **tables**: collections of records (rows) structured by columns,
- **columns**: define the type and purpose of each data field,

- **schemas**: logical groupings of tables and other database objects,
- **views**: output of a defined query on database table (virtual table).

To ensure data integrity and consistency, relational databases use constraints such as:

- **primary key (PK)**: uniquely identifies each row in a table,
- **foreign key (FK)**: enforces referential integrity by linking to a primary key in another table,
- **unique**: ensures that all values in a column or combination of columns are distinct,
- **not null**: prohibits null values in a given column.

These constraints facilitate various types of relationships:

- **one-to-one**: each row in table A links to exactly one row in table B.
- **one-to-many (or many-to-one)**: one row in table A links to multiple rows in table B.
- **many-to-many**: implemented through join tables that associate rows between two tables.

This conceptual framework underpins the database migration described in the following sections.

2.2 Database structure

The current state of SB9 catalog is composed of plain-text files, each representing a separate table and using pipe-separated values (`|`) as delimiters. Although these files already mimic a relational design, the structure lacks formal constraints and consistency enforcement.

The tables include:

- `Main.dta` – basic system information (coordinates, magnitudes, spectral types)
- `Orbits.dta` – orbital elements (period, eccentricity, velocity amplitudes, etc.)
- `Alias.dta` – cross-identifications from other astronomy catalogs

- `Notes.dta` – supplemental annotations per orbit,
- `RadVel (rep)` – radial velocity measurements, one file per system containing several orbital determinations.

For the newer version of the catalog, the database structure has been modified. 2.1, 2.2, 2.3 and 2.4 show a comparison of SB9 table structure to their new one. Some fields have been renamed for clarity, while some other fields are extending the database (e.g. position coordinates in new *systems* table), making the most out of Gaia DR3 survey Collaboration et al. (2016). Finally two tables have been added, *duplicates* holding identifiers of previously found SB9 duplicate systems and *configurations* carrying structure of multiple systems.

To migrate the catalog into a more robust environment, the data was ported to an SQL database. This structure introduces schema constraints—such as data types, primary keys, and foreign keys—that improve consistency during data entry and support reliable relational operations. For example, a composite primary key `(sn, on)` is defined in the `orbits` table to uniquely identify each orbit within a system. The `velocities` table uses a composite foreign key referencing `orbits(sn, on)` to enforce a one-to-many relationship between orbits and radial velocity measurements. In the `alias` table, a combination of `(sn, catalog_name, catalog_version, identifier)` is required to be unique. These constraints facilitate data integrity, eliminate ambiguity, and ease downstream querying and analysis. The overall structure and constraints of SBX schema are illustrated in figure 2.1.

2.3 Data Preparation

Before populating the structured SQL database, it was necessary to clean and normalize the legacy data form SB9, which were affected by numerous inconsistencies. The original tables were manually maintained in pipe-separated text files, often appended through manual entry or (most likely) attempts of automatic extraction using optical character recognition (OCR) algorithms on older, scanned, publications). This led to a variety of issues that would break type constraints or relational integrity if imported directly into a DBMS.

Among the most common problems were:

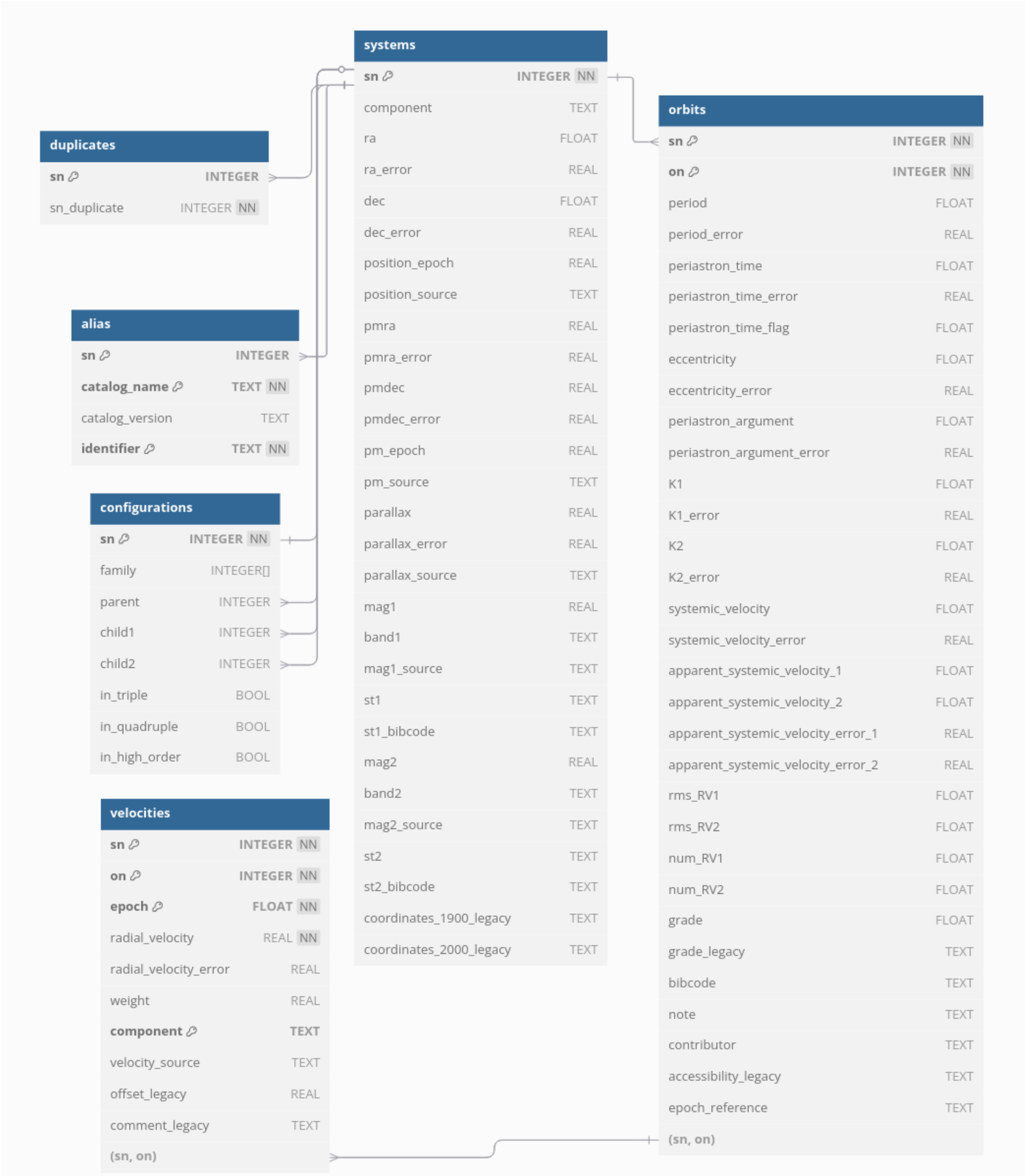

Figure 2.1: Diagram of SBX databse, made using online tool dbdiagram.io

Table 2.1: Field-by-field comparison of previous SB9 *main* table to SBX structure

#	SB9 Field	SBX field	Description
1	System number	sn	Unique system ID
2	Component	component	Spectroscopic component label
3	/	ra	Right ascension [deg]
4	/	ra_error	Error on RA [mas]
5	/	dec	Declination [deg]
6	/	dec_error	Error on Dec [mas]
7	/	position_epoch	Epoch of coordinates
8	/	position_source	Source of coordinates
9	/	pmra	Proper motion in right ascension [mas/yr]
10	/	pmra_error	Error on pmra [mas/yr]
11	/	pmdec	Proper motion in declination [mas/yr]
12	/	pmdec_error	Error on pmdec [mas/yr]
13	/	pm_epoch	Epoch of proper motion
14	/	pm_source	Source of proper motion
15	/	parallax	Parallax [mas]
16	/	parallax_error	Error on parallax [mas]
17	/	parallax_source	Source of parallax
18	Magnitude 1	mag1	Magnitude of component 1 [mag]
19	Filter 1	band1	Band for mag1
20	/	mag1_source	Source for mag1
21	Spectral type 1	st1	Spectral type of component 1
22	/	st1_bibcode	Reference for st1
23	Magnitude 2	mag2	Magnitude of component 2 [mag]
24	Filter 2	band2	Band for mag2
25	/	mag2_source	Source for mag2
26	Spectral type 2	st2	Spectral type of component 2
27	/	st2_bibcode	Reference for st2
28	1900 coordinates	coordinates_1900_legacy	Legacy string format (1900)
29	2000 coordinates	coordinates_2000_legacy	Legacy string format (2000)

Table 2.2: Field-by-field comparison of previous SB9 *orbits* table to SBX structure

#	SB9 Field	SBX field	Description
1	System number	sn	Unique system ID
2	Orbit number	on	Orbit ID within system
3	Period	period	Orbital period [day]
4	Error on P	period_error	Error on period [day]
5	Periastron time	periastron_time	Periastron Time (JD-2400000)
6	Error on Periastron	periastron_time_error	Error on periastron time
7	Flag on periastron	periastron_time_flag	JD/MJD format flag
8	Eccentricity	eccentricity	Orbital eccentricity
9	Error on ecc.	eccentricity_error	Error on e
10	Argument of periastron	periastron_argument	Argument of periastron [deg]
11	Error on argument of periastron [deg]	periastron_argument_error	Error on ω
12	K1	K1	Radial velocity semi-amplitude of component 1 [km/s]
13	Error on K1	K1_error	Error on K1 [km/s]
14	K2	K2	Radial velocity semi-amplitude of component 2 [km/s]
15	Error on K2	K2_error	Error on K2 [km/s]
16	Systemic velocity	systemic_velocity	Systemic radial velocity [km/s]
17	Error on V0	systemic_velocity_error	Error on systemic radial velocity [km/s]
18	/	apparent_systemic_velocity_1	apparent systemic velocity of component 1 [km/s]
19	/	apparent_systemic_velocity_error_1	Error on apparent systemic velocity of component 1 [km/s]
20	/	apparent_systemic_velocity_2	Apparent systemic velocity of component 2 [km/s]
21	/	apparent_systemic_velocity_error_2	Error on pparent systemic velocity of component 2 [km/s]
22	rms RV1	rms_RV1	Standard deviation of residuals on radial velocity measurement for component 1 [km/s]
23	rms RV2	rms_RV2	Standard deviation of residuals on radial velocity measurement for component 2 [km/s]
24	Number RV1	num_RV1	Number of radial velocity measurements for component 1
25	Number RV2	num_RV2	Number of radial velocity measurements for component 2
26	Grade	grade_legacy	Orbit quality (0–5)
27	/	grade	New orbit quality ranking (to be developed)
28	/	note	Notes about the orbit (remarks, references...) → merge of SB9 *Notes* file
29	Bibcode	bibcode	Reference to source publication
30	Contributor	contributor	Contributor
31	Accessibility	accessibility_legacy	Legacy access flag
32	Epoch reference	epoch_reference	JD or MJD

Table 2.3: Field-by-field comparison of previous SB9 *RadVel (radial velocities)* table to SBX structure

#	SB9 Field	SBX field	Description
1	System number	sn	Unique system ID
2	Orbit number	on	Orbit ID within system
3	Epoch	epoch	Julian date of observation
4	Radial velocity	radial_velocity	Measured radial velocity [km/s]
5	Error on RV	radial_velocity_error	Error on measured radial velocity or O-C (difference between observed and computed)
6	Weight	weight	Weight for this radial velocity point
7	Component	component	Component 1 or 2
8	Source	velocity_source	Source for measurement
9	Offset	offset_legacy	Legacy offset
10	Comment	comment_legacy	Notes or flags

Table 2.4: Field-by-field comparison of previous SB9 *alias* table to SBX structure

#	SB9 Field	SBX field	Description
1	System number	sn	Unique system ID
2	Catalog name	catalog_name	e.g. HD, HIP, Gaia
3	Catalog ID	identifier	Identifier in catalog
4	/	catalog_version	Edition or release (new)

- Use of inconsistent notations: missing values represented by dashes `-`, double dashes `--`, or even words like (fixed) for error fields e.g. for a circular orbit where the eccentricity in zero by construction,
- typographic substitutions: digit `0` misinterpreted as the letter `O`, and vice versa, e.g. for the spectral type.
- incorrect use of decimal delimiters (”,” instead of ”.”)
- erroneous encoding caused by OCR errors : value replaced (or even omitted) by its neighbor in the table of original publication,
- numerical fields formatted with text characters, such as exponents like `12.D0`, greater-than signs >, or colons `:`, usually meaning an uncertainty on the value,
- bibliographic references sometimes appended to free-text notes instead of their dedicated reference column, making parsing ambiguous,
- inconsistent column counts across rows, especially in the `radial velocities` and `orbits` tables,
- ambiguous or missing reference identifiers for radial velocity measurement.

The above mentioned inconsistencies made a direct import into a relational database infeasible: SQL type checking, NOT NULL enforcement, and field-specific constraints would fail. Prior to migration, custom scripts were developed to:

- standardize placeholders for missing values (e.g., replace `--`, `-`, `(fixed)` with empty strings or NULL),
- split or recombine text-based fields (e.g., moving embedded bibcodes[1] into dedicated columns),
- clean malformed numeric fields and remove non-numeric characters from expected numeric columns,
- normalize references to match valid bibcodes,
- validate consistency in the number of columns per row.

These preparatory steps were essential to ensure that the final dataset could be parsed, cast to proper data types, and loaded into a constraint-enforced SQL environment without failure.

Many of these corrections required consulting the original publications to verify the published data. It is likely that certain types of errors—such as typographical mistakes by encoders or OCR-related misreadings—have recurred over time as SB9 has accumulated records. Given that much of the data originates from older articles available only as scanned documents, this represents a major limitation. Systematically reviewing all SB9 entries would require a high degree of automation, which remains extremely challenging when working with documents originally intended for human interpretation rather than machine processing.

Fortunately modern techniques help a lot in mitigating those kinds of errors. In that way, SB9's *main* table has been extended and updated thanks to Gaia DR3 survey from which data could be directly queried through Gaia Archive database with SQL commands.

[1] A Bibcode is a 19-character bibliographical code, unique and traceable with the format YYYYJJJJJVVVVPA, commonly used to identify astronomical and physics literature. (Y: year, J: journal, V: volume, P: page, A: author)

2.4 Data Update and Extension

To improve the quality and precision of SBX catalog, SB9 data were systematically updated using external astrometric catalogs. The most significant upgrades were applied to the *systems* table, targeting core parameters such as coordinates, proper motions, parallax, and magnitudes.

The primary source for updated astrometry was Gaia Data Release 3 (DR3) Vallenari et al. (2023), queried through the Gaia archive TAP service (see Chapter 4). For systems with Gaia identifiers, the following fields were directly extracted: right ascension, declination, errors on both, proper motion components and their errors, parallax and its error, as well as the Gaia photometric magnitude, called the G magnitude or G band. All Gaia-derived values were tagged with the epoch 2016 and cited accordingly.

The cross-match between SB9 systems and Gaia DR3 sources was not performed as part of this work but was provided as an input dataset. It followed a rigorous methodology involving epoch propagation from J2000.0 to J2016.0, large-radius cone searches, and ambiguity classification (e.g., one-to-one, one-to-many). This approach ensured both high precision and a low rate of mismatches, enabling confident association of SB9 systems with Gaia entries. A total of 3981 systems were matched, and the results were integrated into the SB9 database structure.

For systems not present in Gaia DR3—often due to being too bright, too faint, or located in dense stellar fields—the fallback source was the Hipparcos catalog European Space Agency (ESA) (1997). In a few remaining cases where neither Gaia nor Hipparcos provided usable data, the Simbad database Wenger et al. (2000) was used as a last resort.

All sources were clearly tracked in the database through fields such as `position_source`, `pm_source`, and `parallax_source`, enabling traceability of the data provenance. A filtering strategy also prioritized precision and consistency, discarding inconsistent or null fields during import.

Thanks to this enrichment pipeline, the *systems* table now offers a more robust and homogeneous astrometric base, ready to support VO-compliant services and large-scale statistical analysis.

2.5 Choice of DBMS

The choice of a database management system (DBMS) for SB9 was primarily driven by practical considerations, rather than by constraints related to scale or performance. The current size of the catalog is relatively modest—on the order of a few ten megabytes—and even when expanded with Gaia DR3 parameters or future orbit contributions, it remains well within the capacity of any standard relational DBMS. That said, the growing volume of data produced by automated sky surveys has been taken into account to ensure scalability. In particular, the upcoming release of Gaia Data Release 4 (DR4) is expected to significantly increase the number of available high-precision measurements (Gaia Collaboration 2025).

Evaluation Criteria

Given the lack of computationally intensive queries or real-time update needs, several open-source solutions could have been suitable, including MySQL, MariaDB, and PostgreSQL (The PostgreSQL Global Development Group (2024)). All of these support basic relational operations, type constraints, and indexing strategies required by our data model.

Motivations for PostgreSQL

PostgreSQL was ultimately chosen for several reasons:

- it is widely adopted in the astronomy community, notably by the Gaia archive maintained by ESA,
- it supports advanced features such as array types, extensions like `pg_sphere` for spherical coordinates, and robust type checking—all of which are useful for astronomical catalogs,
- ADQL (Astronomical Data Query Language) capabilities (see 4) required for Virtual Observatory compliance have been implemented and tested in available libraries with PostgreSQL backends.

This combination of technical compatibility and community precedent made PostgreSQL a natural choice for hosting the updated SB9 data.

Finally PostgreSQL is -among others- suited for use within web applications which is a key requirement for the renewing of SB9 website.

Chapter 3

Website Set-up

3.1 Limitations of the Legacy Interface

The original SB9 website relies on server-side CGI scripts and a set of bash pipelines to handle user input, data lookup, and output formatting. This architecture, though functional, suffers from several limitations. The interface is rigid and unforgiving—prone to failure when encountering non-standard input—and lacks tolerance for aliases or partial identifiers. Graphs are generated on-the-fly using PostScript, an outdated format for modern web browsers. From a maintainability standpoint, the absence of separation between data access, domain logic, and interface design makes updates both time-consuming and error-prone.

3.2 Goals and Requirements for the New Website

The updated website is designed to address these limitations and bring SB9 into alignment with modern web standards. The principal requirements include:

- A responsive and user-friendly interface.
- A more powerful and flexible search engine.
- Dynamic and exportable plotting tools for radial velocity curves.
- Downloadable data products in standard formats.
- A submission portal allowing researchers to upload new orbit solutions.
- Integration with Virtual Observatory standards (TAP, ADQL).

3.3 Architecture and Design Choices

To support these goals, the new website is being developed according to a three-tier architecture:

- **Presentation layer**: the front-end interface, currently a minimal but expandable HTML+CSS design.
- **Logic layer**: the application logic implemented in Python using the Django framework.
- **Data layer**: the PostgreSQL database containing the structured SB9 data.

This separation of concerns allows the interface to evolve independently of the database structure, and facilitates more robust testing and scaling.

3.4 Django Framework

The Django framework Django Software Foundation was chosen for several reasons:

- it is Python-based, aligning with the language ecosystem most familiar for the community,
- it offers built-in ORM (Object-Relational Mapping[1]), making database queries both readable and secure,
- it integrates naturally with scientific Python tools such as `matplotlib` for plotting, `numpy/pandas` for data handling, and `astropy` for astronomical utilities,
- it includes a flexible forms API and a robust user authentication system, which are useful for future features such as orbit submission and user feedback.

3.5 Current State of Development

As of now, the back-end database and logic layers are operational. Users can browse systems, orbits, and radial velocity plots through a basic HTML interface. Plotting is handled server-side using `matplotlib`, and measurements can be downloaded in CSV format.

[1]a convenient way of bridging SQL database to object-oriented programming language for data manipulation

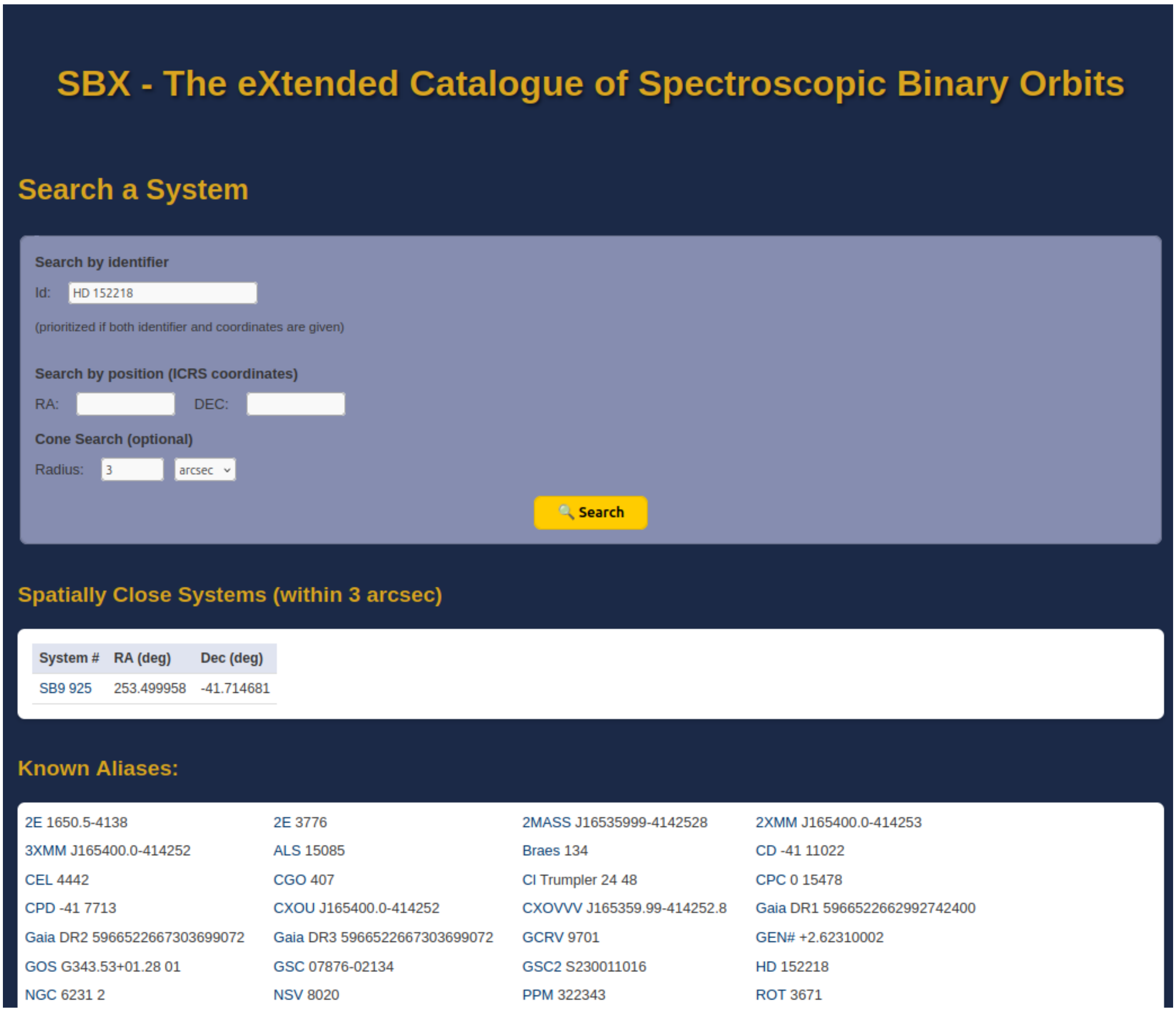

Figure 3.1: Basic search of an element through SBX new website with cone search. The element is known in the database: equivalent identifiers are shown and other astronomical object in the cone search are displayed.

Search Engine

The new search engine replaces the legacy SB9 lookup tool with a more resilient and versatile query system built in Django. It supports multiple layers of lookup strategies to increase robustness, user tolerance, and integration with external databases. Figure 3.1 shows a query of a system through SBX search engine.

The engine accepts both identifier-based queries (e.g., system numbers, external catalog names like `HD 12345`) and coordinate-based searches via cone search. Users can input coordinates in right ascension and declination. In both case a ”cone search” is possible ie search for an astronomical object or a position and all other objects around it up to an angle of aperture set by the user.

For identifier searches, the logic follows a hierarchical approach:

1. Direct system number (sn) lookup, including automatic redirection from known

duplicates.

2. Exact match on catalog aliases (`catalog_name`, `catalog_version`, `identifier`).

3. Fuzzy matching of aliases using string similarity scores, allowing partial or misspelled input.

4. Integration with the Sesame name resolver service maintained by the Centre de Données de Strasbourg (CDS), which suggests external aliases that are cross-matched against the local database.

To handle ambiguities in catalog notation, the system normalizes input by unifying casing, whitespace, and catalog-specific formats (e.g., merging `BD -06` into `BD-06`). These steps ensure compatibility with both user input and external catalog conventions.

If a matching system is found, the corresponding aliases, astrometric parameters, orbits (and original references), radial velocity values and curve plots are retrieved and rendered. If not, suggestions from Sesame and similar aliases from the local database are displayed to assist the user. The engine is also forward-compatible with future additions, such as name autocompletion.

Orbits Display

The new interface for visualizing orbits provides both graphical and quantitative representations of the radial velocity (RV) measurement for a given binary system. The implementation is based on a Django view that retrieves orbital parameters and velocity measurements generates plots using `matplotlib`.

For each orbit, a synthetic radial velocity curve is computed from the published orbital elements. Two types of plots are produced:

- **RV vs. Time**: showing both observed data (with error bars) and the modeled curves over time.

- **RV vs. Orbital Phase**: folding the data and model over the orbital period to highlight periodicity and phase coverage.

If both K_1 and K_2 are available, the system is treated as a double-lined spectroscopic binary (SB2), and both components are modeled. If only one amplitude is known, it is treated as an SB1.

The backend also computes physically relevant derived quantities, including:

- The projected semi-major axis of the primary component, $a_1 \sin i$.
- The mass function $f(m)$ in solar mass units.
- The mass ratio q = $M_2/M_1 = K1/K_2$, if both amplitudes are known ($M_{1/2}$ being respectively the mass of the primary/secondary star).

Uncertainties on these quantities are propagated analytically from the errors on P, K_1, K_2, and e when available.

Finally, users can download the original RV measurements in CSV format directly from the orbit detail page. This makes the interface not only a visualization tool, but also a gateway for downstream scientific reuse of the data. Figure 3.2 shows how orbital parameters are displayed in SBX website with radial velocity measurement plots.

Front-End

The front-end remains simple but was designed with extensibility in mind. Interactive plots (e.g., via JavaScript or Plotly Plotly Technologies Inc. (2025)) and advanced filtering options are among the planned enhancements. A submission form for new orbits is under development and will offer both manual input and file upload options, backed by data validation before insertion into a secondary review schema.

Domain Logic Structure

The web application is developed using the Django framework, which promotes a modular organization into independent apps, each handling a specific domain of functionality. The project is divided into three main Django apps—`home`, `catalog_check`, and `orbit_submission`—alongside a global configuration in the root module `web_sb9`.

A simplified view of the project structure is shown below:

```
web_sb9/                    ← Project configuration (settings, routing)
 home/                   ← Home page and static site content
 catalog_check/          ← Core functionality: search, display, plots
 orbit_submission/       ← User-submitted orbit data + validation
 templates/              ← Shared base templates
 manage.py               ← Django management script
```

Each app follows Django's standard conventions:

Figure 3.2: Display of orbital parameters on SBX website with radial velocity plots and possibility to downlaod the measurements.

- **models.py**: database models and field definitions.
- **views.py**: request-handling logic (e.g., orbit plots, search).
- **urls.py**: app-specific route definitions.
- **templates/**: HTML templates scoped to the app.
- **static/**: CSS and image resources.

The `catalog_check` app is responsible for most of the catalog interaction: it implements the search engine, orbit plots, and radial velocity retrieval. The `orbit_submission` app handles user input for new data, using Django forms and a dedicated `db_router.py` to redirect submissions to a separate review database.

All pages share a common HTML base template located in the top-level `templates/base.html`, and user authentication is provided via Django's built-in system with a login form in `templates/registration/login.html`.

This modular architecture ensures that different parts of the application can evolve independently and encourages clear separation of concerns between logic, presentation, and data.

Chapter 4

TAP Service

4.1 Virtual Observatories and the IVOA

The International Virtual Observatory Alliance (IVOA) is an international organization that develops technical standards to enable global and interoperable access to astronomical data. Its goal is to ensure that data from different observatories and archives can be queried, exchanged, and analyzed using shared protocols.

Virtual Observatories (VOs) are platforms that adhere to these IVOA standards, allowing astronomers to access heterogeneous datasets through common interfaces, independent of their original source or format. These frameworks are crucial in modern astronomy, where federated and automated access to large, distributed datasets is essential.

4.2 ADQL and TAP Protocol

To support such interoperability, the IVOA has defined a set of protocols and query languages. Among these, the Table Access Protocol (TAP) is designed to allow access to astronomical databaseDemleitner et al. (2019)s using a standardized query interface. TAP queries are written in the Astronomical Data Query Language (ADQL Ortiz et al. (2008)), which is a SQL-like language with extensions for astronomical operations such as cone searches and coordinate system transformations. Enabling efficient and precise queries on celestial coordinates and metadata, regardless of the database backend.

4.3 Motivation for SB9 TAP Deployment

During a technical meeting with researchers from the Centre de Données astronomiques de Strasbourg (CDS), it was recommended that SB9 adopt a TAP interface to simplify integration with existing services and tools. The informatician in charge of maintaining the SB9 data at CDS, specifically advised the transition to a TAP service, both to facilitate their internal workflows and to align with current Virtual Observatory practices.

The SB9 catalog is already hosted on the CDS VizieR platform[1], which provides static access to its data tables. However, the absence of a TAP service limits its integration with dynamic querying tools and VO-compliant pipelines. By implementing TAP, SB9 aligns with IVOA standards, significantly increasing the catalog's accessibility, encouraging reusability by external researchers, and easing automated cross-catalog analyses.

The deployment of a TAP interface also improves SB9's visibility within the Virtual Observatory network, reduces the friction of third-party tool integration (e.g. Topcat), and ensures long-term maintainability through adherence to shared protocols.

4.4 Implementation Using CDS Library

The TAP service for SB9 was implemented using a lightweight and standards-compliant TAP server library named *Vollt* developed at CDS Mantelet (2023). This library includes a full ADQL parser and handles request dispatching, query execution, and metadata publication.

Our deployment uses PostgreSQL as the backend and maps the SB9 tables to a VO-compliant TAP schema. ADQL queries are parsed and translated to native SQL, executed against the database, and returned in various format such as text, .csv, VOTable...

The Vollt library is developed in the Java programming language Arnold et al. (2005) and is designed to run as a web application. It therefore requires a web server capable of executing Java-based services. Since the library was originally tested on an Apache Tomcat server (The Apache Software Foundation), this environment was also adopted for the SBX TAP service. The application can be deployed with minimal effort using a configuration file, allowing for a quick and functional setup of the TAP service.

As of now this service is publicly accessible (as shown in figure 4.1) even though it

[1] https://cdsarc.cds.unistra.fr/viz-bin/cat/B/sb9

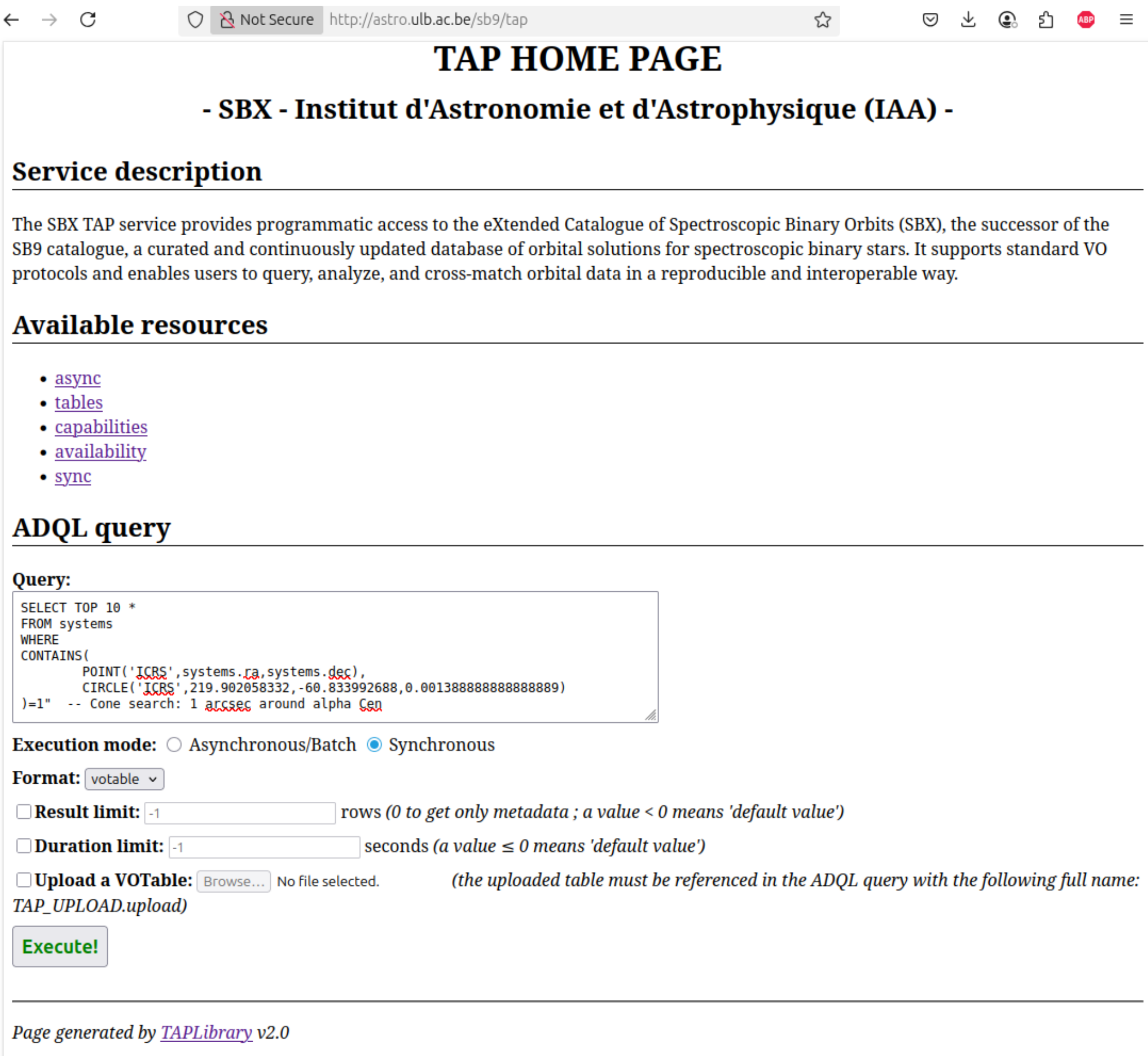

Figure 4.1: SBX TAP service user interface. Currently accessible online at www.astro.ulb.ac.be/sb9/tap

is not up to date with the latest catalog version yet.

Chapter 5

Conclusion and Perspectives

This work has laid the foundation for a major transformation of the SB9 catalog of spectroscopic binary orbits into a more durable, accessible, and interoperable resource. Through the adoption of a relational database system, extensive data cleaning and updating, integration of high-precision astrometry from Gaia DR3, and the implementation of a web-based search engine and TAP service, the catalog has evolved into what is now referred to as SBX—the eXtended Catalogue of Spectroscopic Binary Orbits.

The deployment of a TAP interface aligned with IVOA standards ensures greater visibility and compatibility with Virtual Observatory tools, improving the catalog's reusability across the astronomical community. The transition to a modern infrastructure also enables more efficient data querying, enhanced cross-matching, and streamlined updates.

However, the modernization process is not a one-time task, but rather the beginning of a project on the long run. Several developments remain beyond the scope of this work but might be beneficial for the future of SBX. These include:

- the development of a more advanced and interactive front-end, offering richer visualization and exploration tools for binary orbits and radial velocities;
- the deployment of mirror servers to ensure availability and redundancy in case of outages;
- full compliance with IVOA service registration protocols and metadata standards, enabling official integration into the Virtual Observatory ecosystem;
- user submission and moderation workflows for orbit updates to ensure community-driven sustainability.

Finally, it is worth noting that deploying and maintaining a scientific website is a complex and ongoing effort. Ensuring uptime, responding to bug reports, maintaining database integrity, and adapting to evolving standards all require time and technical support well beyond the time window of a master thesis. This work thus represents a starting point, offering both a functioning prototype and a scalable architecture to support future developments by the broader community.

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