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S_{B^9}: The Ninth Catalogue of Spectroscopic Binary Orbits

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Abstract. The Ninth Catalogue of Spectroscopic Binary Orbits (http://sb9.astro.ulb.ac.be) continues the series of compilations of spectroscopic orbits carried out over the past 35 years by Batten and collaborators. As of 2004 March 1st, the new Catalogue holds orbits for 2 381 systems. Some essential differences between this catalogue and its predecessors are outlined and three straightforward applications are presented: (1) Completeness assessment: period distribution of SB1s and SB2s; (2) Shortest periods across the H-R diagram; (3) Period-eccentricity relation.

1. Introduction

Over the past fifteen years the Eighth Catalogue of the Orbital Elements of Spectroscopic Binary Systems (SB8, Batten et al. 1989) has been used extensively by the community for a variety of purposes ranging from binary statistics to target selection. It is referenced by more than one hundred papers in the literature. The progress of the spectro-velocimeters (CORAVEL, CfA speedometers, etc.), which have significantly increased the number of known late-type spectroscopic binaries, combined with the need for refined statistics, have made the revision of the 8th catalogue worth undertaking. At the 2000 IAU General Assembly in Manchester, Commission 30 decided to take responsibility for the 9th catalogue (S_{B^9}). We report on the progress achieved so far. The main goal is to make potential users aware of this new database and its features. In the process of compiling it, we have also found that it often serves to correct mistakes of various kinds that have gone unnoticed in the original publications.

Catalogues of spectroscopic binary orbits are used in many very different ways. For example, they serve to select specific types of binaries for further observations, such as the compilation by Taylor et al. (2003), which is aimed at selecting interferometrically resolvable systems. A combination of SB8 with visual-binary and other catalogues has lead to the creation of the database on high-multiplicity stars (Tokovinin 1997). Spectroscopic binaries with detectable motion received special processing during Hipparcos data reduction (ESA 1997), and this is anticipated to be even more important for the next generation of astrometric satellites such as Gaia (Pourbaix & Jancart 2003) or SIM (Marr 2003). Evidently, a catalogue also serves for various statistical studies. In the past, controversial results on the mass ratio distribution were obtained from SB catalogues (see the discussion in Duquennoy & Mayor 1991), and in recent years volume-limited samples have been much preferred for this kind of analysis (e.g., Heacox 1998; Halbwachs et al. 2003). Despite strong and poorly known selection effects, SB catalogues are nevertheless indispensable for certain types of statistical work where the large number of objects is of primary importance. This is the case, for example, when there is a need to define various boundaries in the orbital-parameter space or when only a small sub-sample of objects with specific properties is studied, such as chemically peculiar stars or late-type giants (Boffin et al. 1993). Finally, binaries with unusual properties are best found in such large catalogues.

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The content of S_{B^9} in terms of orbits, and the matching of S_{B^9} with other major catalogues is described in Sect. 2, while the differences with respect to previous compilations are outlined in Sect. 3. Sect. 4 presents two different ways of accessing the data. We conclude in Sect. 5 with three applications, of which two rely upon S_{B^9} only and the other illustrates the benefit of joining it with other major catalogues such as Hipparcos.

2. Content

By definition the content of S_{B^9} changes almost continuously, and users always access the latest version in real time. Let us nevertheless freeze the content at, say, May 1st 2004, i.e., almost three years after SB8 was used as a seed for its successor.

S_{B^9} contains 2 381 systems (versus 1 469 in SB8) for a total of 2 684 orbits. A system can be represented by either two stars or one star and the center of mass of another system. A triple star is thus seen as two distinct systems identified through the component descriptor. There are 55 spectroscopic triple (or higher multiplicity) systems and eight systems with up to four orbits.

In terms of cross-references with other catalogues, 732 S_{B^9} systems are included in the GCVS (Kholopov et al. 1998) and 1 825 in the Hipparcos catalogue (ESA 1997). The large overlap with Hipparcos is a selection effect, as illustrated in the left panel of Fig. 1; so far, S_{B^9} systems are predominantly bright objects. By incorporating the Hipparcos parallaxes, the spread of the systems over the Hertzsprung-Russell (H-R) diagram is shown in the right panel of Fig. 1.

The completeness of the database can be evaluated through the number of published orbits that are still missing. According to the Bibliographic Catalogue of Stellar Radial Velocities (Malaroda et al. 2003), about 545 papers with orbital solutions published prior to 2003 still need to be uploaded (this is in addition to the 363 papers already added after SB8). These 545 papers are expected to yield some 1 500 orbits out of which $\sim$1 200 might be new systems. While the work of Malaroda and collaborators is certainly very useful, the actual number of missing papers is somewhat difficult to evaluate. For example, we have found and reported a few entries in their catalogue that have no orbit in the original publication despite the 'ORB' flags in their entries. In addition, there is a gap between the date of the most recent SB8 orbit and the earliest paper in their catalogue. Sporadically we still find systems whose orbit was published much earlier than the completion of SB8 and that were nevertheless absent from that compilation.

3. Major differences with respect to SB8 and predecessors

For both the SB8 catalogue and the current version of the S_{B^9} catalogue we have plotted in Fig. 2 the number of systems versus $B-V$ color. The primary source for the colors was the Hipparcos catalogue. For stars not in that catalogue, the SIMBAD database was used. The shaded histogram for SB8 shows 98% of its systems. The completeness for S_{B^9} is somewhat less, 94%, at least in part because of a significant increase in X-ray binaries. Despite this modest disparity in completeness, the comparison of the two distributions is instructive. The histogram for the SB8 catalogue shows a peak in the $B-V$ distribution corresponding to late-B and early-A type stars, and then a relatively uniform decline in the number of systems with increasing $B-V$ color.

The distribution of systems in S_{B^9} is rather different. The strength of the peak for the early-type stars is little changed from that in SB8, while the number of late-type systems has increased dramatically. The strongest peak currently occurs for colors that correspond to a range of mid-F to mid-G stars. Redward of this peak, there is a significantly enhanced tail that extends to about $B-V=1.3$. This tail contains numerous evolved stars, including barium stars and chromospherically active binaries. At least part of the large increase in the number of late-type binaries may be attributed to the advent of velocity spectrometers such as CORAVEL and the CfA speedometers, which are most productive for late-type stars. With the eventual addition to S_{B^9} of several hundred systems that currently have published orbits, we expect the number of late-type binaries to continue its rapid rise. Over the next few years orbits for a substantial number of M giant symbiotic binaries also will be determined, extending the tail.

In previous versions of the Catalogue the aim was to provide a single 'best' orbit per system even though several different orbits were often discussed in the notes. S_{B^9} lists all available orbits, whether they turn out to be wrong, preliminary or definitive. The grade associated with a given orbit (following the practice in previous catalogues) should help the user select the best quality solution if only one orbit is needed. The number of identifiers that can be stored for a given system in S_{B^9} is unlimited, unlike previous editions, although the major catalogues (e.g., HD, DM, HIP, …) are still favored as the source for stellar identification.

For the present Catalogue the 2000.0 epoch/equinox was adopted rather than 1900.0, and the number of digits in the coordinates was also increased in order to match the precision adopted by other compilations (e.g., the Washington Double Star Catalog; Mason et al. 2001). Positions are now given to the hundredth of a second of time in Right Ascension and to the tenth of a second of arc in Declination. The 1900.0 coordinates initially kept for backward compatibility have now been discontinued.

The orbital parameters are listed in the Catalogue together with their published uncertainties. For some double-lined systems where separate values of the eccentricity and the systemic velocity were reported for each component in the original publication, it was decided to store only one set, even though this may cause difficulties in some cases. The second set of values is usually listed in the notes.

The main difference between S_{B^9} and its predecessors has to do with the data used to derive the orbits. Whenever possible, all the radial velocities used for an orbit are also stored in S_{B^9}. Situations where this is not possible are already foreseen (e.g., orbits fitted directly to spectra, without the determination of radial velocities, etc.). Nevertheless, an effort is made to be as complete as possible for orbits published until now, and radial velocities for 1 113 systems have been included, even for or-

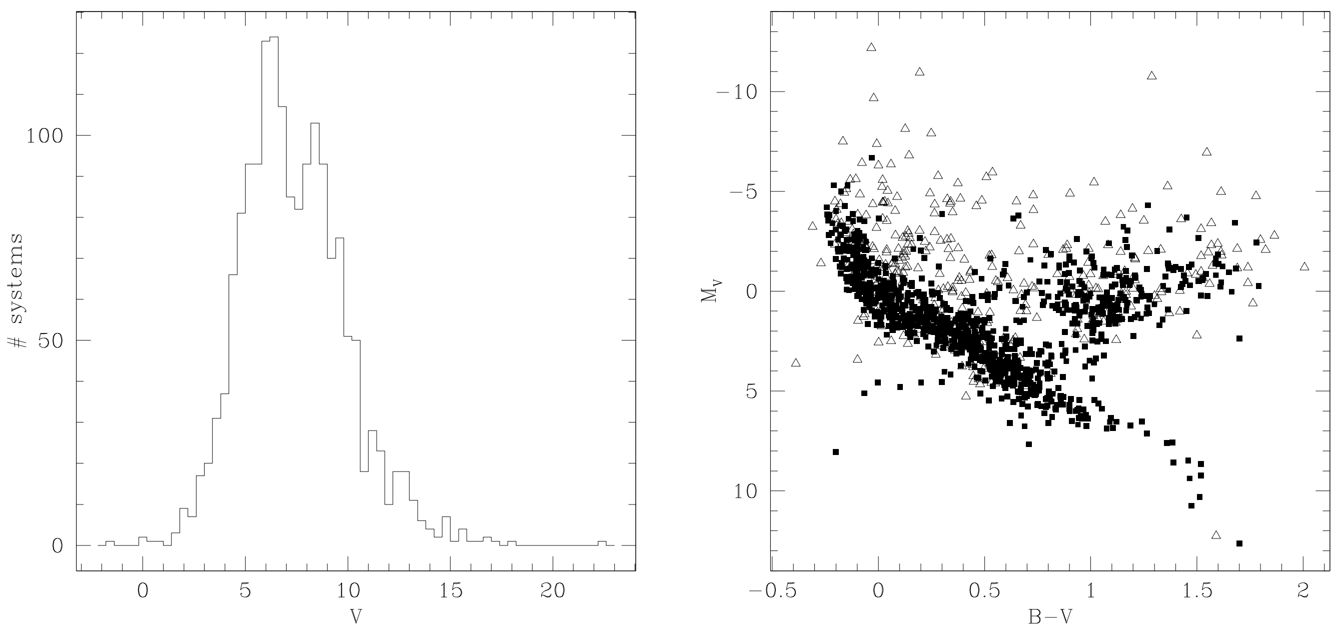

Fig. 1. Left panel: Distribution of the apparent V magnitude for all S_{B^9} systems. **Right panel:** H-R diagram of the 1 825 S_{B^9} systems after Hipparcos. Filled squares denote 3σ parallaxes whereas open triangles denote less reliable ones.

bits already present in SB8. Although collecting individual radial velocities is very time consuming, their availability makes it possible to double-check both the transcribed orbit and the one published in the literature. Authors are notified when typographical errors are noticed in the original paper, if possible.

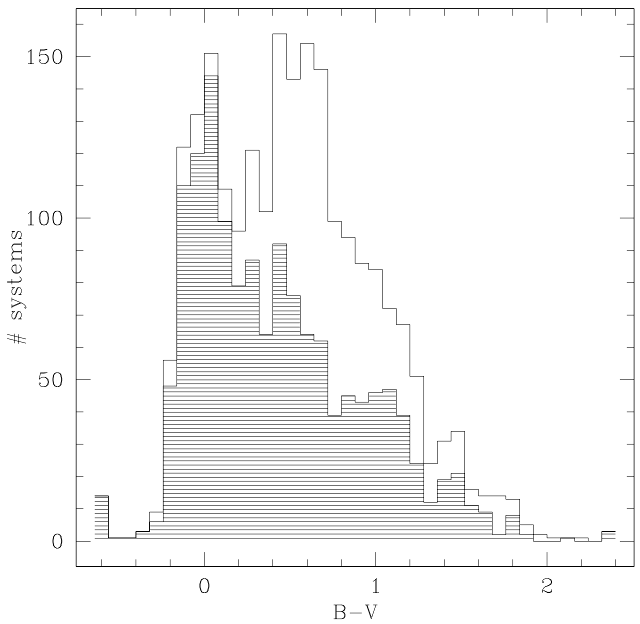

Fig. 2. Distribution of $B - V$ colors for S_{B^9} (resp. SB8) systems as empty (resp. shaded) histograms.

Since more than one orbit can be listed, it is possible to identify which systems from SB8 have been reinvestigated. A total of 177 SB8 systems are listed with two or more orbits, and 13 of them had orbits which were already considered definitive in SB8 (55 entries). Thus, $\sim$25% of the best systems have been investigated again. Unfortunately, at the other end of the quality range only 6% of the low quality orbits have been revised. One might therefore conclude that users are more interested in identifying new systems than in refining those already known but still poorly modeled.

The bibliographic reference for an orbit is given by the 19-character bibliography code (”bibcode”) used by the NASA Astrophysics Data System (ADS). When no bibcode is available for an orbit, a special code is substituted to indicate that the reference is listed in the Notes part of the Catalogue.

4. Access

A direct consequence of the unlimited number of orbits and identifiers that can be stored was the replacement of the single table used in SB8 with a relational database structure (several tables). Whereas a basic selection (or simply printing) is perhaps more difficult than with a unique table, such a structure is much more flexible.

The most convenient way to access S_{B^9} and to browse a specific orbit is through its web interface[1]. Systems can be searched by catalogue identifier as well as by coordinates. If several systems match the selection criteria, the user is asked to further select one. If several orbits are available, the user selects one of them for display. The year of publication is listed to aid in making a choice among the orbits.

The displayed information takes advantage of HTML by offering links. Aside from the coordinates, spectral type, appar-

[1] http://sb9.astro.ulb.ac.be/

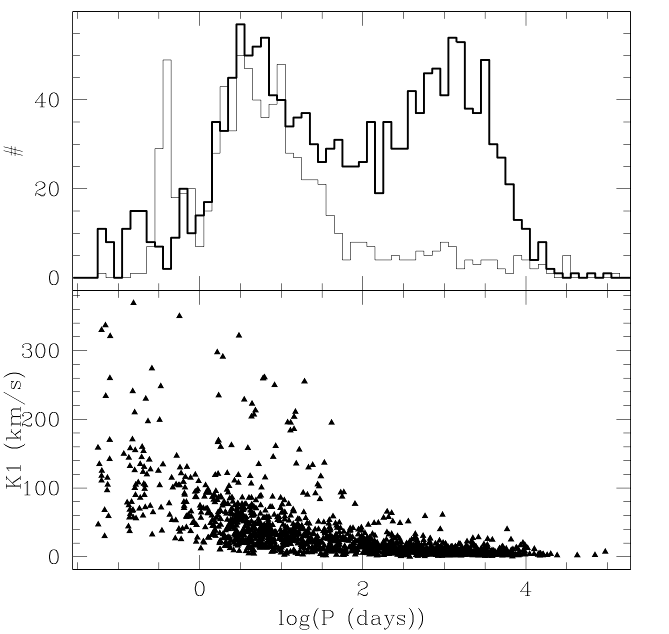

Fig. 3. Top panel: Distribution of the orbital periods in days. The thick (thin) line histogram represents the period of single-lined (double-lined) systems. **Bottom panel:** Amplitude of the radial velocity curve as a function of the orbital period for single-lined systems.

ent magnitude, identifiers, orbital parameters, and other information, the interface offers a direct link to ADS thus allowing straightforward retrieval of the abstract of the paper. The interface also offers the automatic plotting of the orbit (with the actual observations, if available). The corresponding figure is displayed on the screen, and a PostScript version is available as a link.

For researchers interested in properties of a sample of these systems rather than in browsing one orbit, a compressed 'tar ball' version of part of the database is also available from the S_{B^9} main page. Only the radial velocity files are missing from that archive. Coupled with Unix-like standard tools such as *sort* and *join*, and popular scripting languages such as *awk* and *python*, the possibilities offered by this distribution of the database combined with other public access catalogues are almost unlimited, as illustrated in Sect. 5.

5. Applications

5.1. Completeness assessment

Although as mentioned in Sect. 2 completeness of S_{B^9} has not yet been achieved, it is still possible to evaluate its statistical completeness. If one aims at a database useful for statistical purposes, the extent to which the present orbits represent the parent population is what matters.

In their statistical studies of F7-K binaries with periods under 10 years, Halbwachs et al. (2003) obtained a bi-modal distribution of the orbital period with peaks at 20 days and $\sim$2 years. Owing to the size of their sample, they could not rule out the possibility that the distribution was actually consistent with a log-normal distribution. In the top panel of Fig. 3 we show the distribution of the periods for both the single-lined (SB1) and double-lined (SB2) systems in S_{B^9} (the latter accounting for 1/3 of the entire database). For single-lined systems the distribution is clearly bi-modal, with peaks at $\sim$4 days and $\sim$1 200 days. While the distribution of periods for SB2 systems appears bi-modal as well, the two only share one peak. Indeed, the latter distribution has a peak at $\sim$0.4 days corresponding to contact binaries.

Can the absence of a peak at $\sim$1200 days in the distribution of SB2 periods be explained as an observational bias? Long orbital periods imply small velocity amplitudes, which are more difficult to detect. To illustrate this, the lower panel of Fig. 3 shows the distribution of semi-amplitudes K_1 for SB1 systems. It is seen that even for periods in excess of 1000 days the semi-amplitudes remain large compared to typical measurement errors in the velocities, so in principle such orbits should still be detectable for SB2s. However, the main difficulty for long-period double-lined systems is blending of the spectral lines. The low amplitudes make it much more difficult to detect the lines of the two components in the first place, let alone disentangle them and measure their velocities. This observational effect is likely to contribute to the paucity of SB2s with long periods. The lack of a peak at 0.4 days for SB1s, however, seems more difficult to explain as an observational bias.

Another striking feature of the bottom panel of Fig. 3 is the behavior of K_1 for periods below 3 days ($\log P < 0.5$). Whereas the distinction between SB1s and SB2s is often just a matter of the magnitude difference between the components, the value of K_1 for a given SB1 system is a function of the orbital inclination: any value down to zero is equally likely. There is an rather clear lack of SB1 systems in the lower left corner of the diagram, although it is too early to tell whether this is real, or the result of observational bias.

5.2. H-R diagram and the shortest periods

While S_{B^9} contains only limited information on each system aside from the orbital parameters (whereas other catalogues such as that by Taylor et al. (2003) list many more properties), its plain text format with simple field delimiters makes it straightforward to join with other tables, e.g., the Hipparcos and Tycho Catalogues (ESA 1997). As an example, let us consider the location of all the systems in the color-magnitude diagram based on the Hipparcos parallaxes and colors, along with the periods from S_{B^9}. What is the shortest possible orbital period for a binary across the H-R diagram? Clearly this period depends on the radius of the star (Roche lobe filling). S_{B^9} makes it possible to investigate this interesting question.

In Fig. 4 we display the shortest periods for each bin of $B - V$. Filled symbols represent the minimum period while the open symbol stands for the third shortest period in that bin. The distance between the two symbols therefore gives an idea of the confidence in that minimum period. For $B - V > 0.7$ there is a distinction between main sequence and giant stars based solely on the absolute magnitude: $M_V > 4$ is considered main-sequence (we make no distinction here between giants and super-giants). Triangles/pentagons represent main-

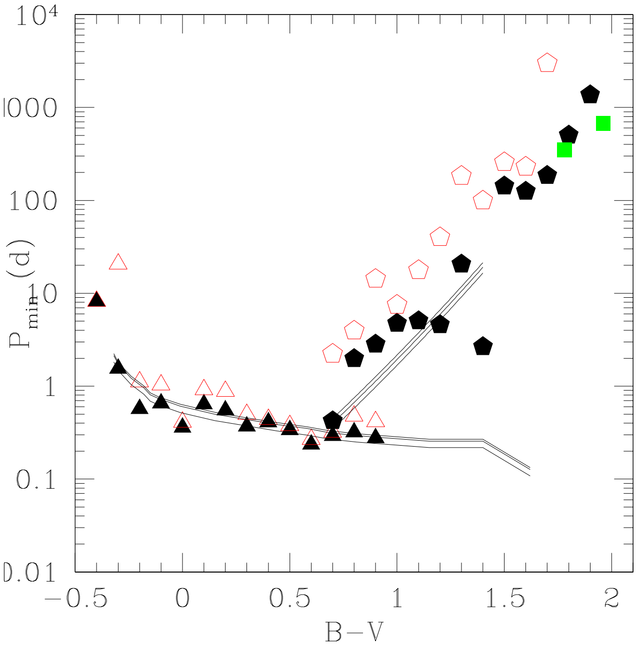

Fig. 4. Minimum and third shortest periods (filled and open symbols, respectively) as a function of $B-V$. Pentagons are for systems not belonging to the main-sequence according to their $B-V$ (>0.7) and their absolute magnitude ($M_V < 4$). The two filled squares are suspected giants missing from the Hipparcos catalogue (ESA 1997).

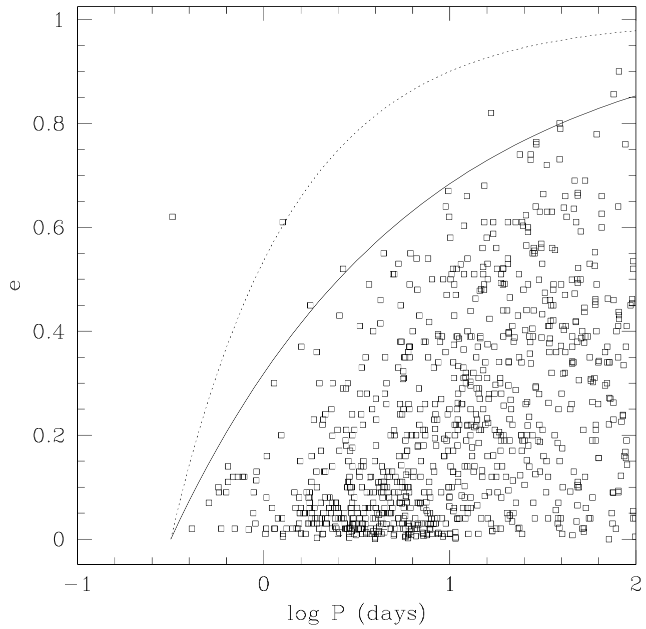

Fig. 5. Period-eccentricity relation for all S_{B^9} objects with $P < 100$d and $e > 0$ (see text).

sequence/giant stars. Owing to the lack of main-sequence stars redward of $B-V = 1$, we omit those points. Two stars thought to be giants but absent from the Hipparcos catalogue are plotted as filled squares.

The tracks in the figure represent the theoretical periods corresponding to systems where one component fills its Roche lobe, with a secondary mass of $0.2m_1$, $0.6m_1$, and $0.9m_1$, where m_1 is the mass of the primary. For the main-sequence curves we use the data after Popper (1980) together with relations from Schmidt-Kaler (1982). The giant tracks are based on a rough estimate of M_{H_p} from Fig. 3.5.5 of the Hipparcos catalogue, with the assumption that $H_p = V$ and a quadratic fit of the bolometric correction vs. $B-V$ from Schmidt-Kaler.

The agreement between the theoretical tracks and the observations is excellent with the exception of one giant star (HIP 9640) with $P \sim 3$ days instead of 20 days. However, this object is a known multiple system. Whereas the primary is indeed a supergiant (thus explaining the pentagon symbol), that star does not belong to the spectroscopic system for which the period is given in S_{B^9}. Therefore, nothing prevents the period from being shorter than inferred from the luminosity class of the whole system.

5.3. Period-Eccentricity

In Fig. 5 we show the period-eccentricity relation for all S_{B^9} objects with $P < 100$ days and non-zero eccentricity. The upper envelope of the data distribution – largest eccentricity for a given period – does not seem to be completely understood. According to current theory the eccentricity is limited either by contact of the components or by tidal effects, both being determined by the distance at periastron $a(1-e) \propto P^{2/3}(1-e)$. In this case the upper envelope would be described by a line $P(1-e)^{3/2} = \mathrm{const}$. Such a law (dashed line in Fig. 5) is not a good match to the data, and the full line $P(1-e)^3 = \mathrm{const}$ describes the envelope much better. The points above the full line correspond to a pulsar PSR 1913+16 (No. 1137 in SB8) and to two orbits of poor quality that are likely erroneous (No. 869 and 353 in SB8). The upper envelope is formed by spectroscopic binaries with early-type (O, B, A) main sequence components, since low-mass binaries tend to be circularized by tidal forces.

There is no apparent explanation for the upper envelope. The constraints on eccentricity derived by Hut (1981) from dissipative tidal evolution lead to a lower limit on the angular momentum of a binary that is again similar to the dashed line, rather than the solid line. Quantities such as angular velocity at periastron or the fraction of the orbit spent near periastron again correspond to the dashed line.

6. Conclusions

Due to our limited manpower for this work and the long delay since the release of SB8, S_{B^9} is still far from achieving an adequate degree of completeness. Despite its 'work in progress' status, the present version of S_{B^9} already offers several advantages over SB8, among which is an increase of 61% in the number of systems listed. Numerous applications should benefit from these increased numbers (e.g., more than 800 double-lined systems await a determination of their individual masses by interferometric means).

Authors of orbital solutions are invited (and indeed urged) to send DP the TEX or LATEX version of their papers for quick upload into S_{B^9}. Tools are also available for those interested in formating their own data prior to inclusion in S_{B^9}.

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