

THE ROTATION OF THE MAIN-SEQUENCE COMPONENTS OF ALGOL-TYPE SEMI-DETACHED ECLIPSING BINARIES*

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Abstract. Newly determined rotational velocities of the main-sequence components of 14 Algol-type semi-detached systems and of 2 detached systems are presented. Combination of these data with the existing data on the rotation of the components of semi-detached systems shows that (i) in systems with primaries of spectral type B8 or later and with $P < 5$ days, deviations from synchronism between rotation and revolution are small in 14 out of 15 cases. The average rotational velocity of the primaries in such systems is 75 km/sec, viz. only 40% of the average rotational velocity of single main-sequence stars in the same spectral region: (ii) primaries of spectral type earlier than B8 in systems with short as well as long periods tend to rotate more than twice as fast as one would expect from synchronism. A tentative explanation for these results is presented.

In close binaries with periods less than about 4 days and with both components on the main sequence the axial rotation of the components is generally observed to be synchronised with the orbital revolution (Plaut, 1959; Olson, 1968). However, in semi-detached Algol-type systems with periods of less than 4 days such a synchronism is not always observed; for instance in the systems of U Cephei (Struve, 1944, 1963) and RZ Scuti (Hansen and McNamara, 1959) the main-sequence components rotate much faster than would be expected in case of synchronism.

Algol-type semi-detached (s-d) systems are expected to be the products of extensive mass exchange in evolving close binaries. During such a mass exchange both the binary period and the rotational angular momentum of the components may change. In the computations of the evolution of close binaries one generally assumes for computational reasons that no exchange between orbital angular momentum of the exchanged matter and rotational angular momentum of the components occurs. However, the above mentioned observations of non-synchronism, as well as computations of particle trajectories in close binary systems (cf. Kruszewski, 1966) show that such an exchange of angular momentum probably takes place in nature. One therefore does not a priori expect the components of s-d systems to rotate synchronously with the orbital motion, especially not during or just after the stage of mass exchange. One may then wonder whether the deviations from synchronism will last for a long time after the mass exchange is terminated, or whether tidal (re-)synchronisation will occur in a fairly short period of time. One may try to answer such a question by examining the rotation of primaries of a random sample of s-d systems, and see how large the percentage of synchronous rotators is. Since the random sample probably will show a random distribution of ages (following the mass exchange stage) the fraction of synchronised primaries in the random sample is then expected to be equal

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TABLE Ia
The 16 Algol-type systems for which the rotational velocities of the primaries were obtained in this investigation^a

No. in SB Catalogue	Name	Spectrum	m_V	Period (days)	v (km/sec)	v_{syn}	$f(m)$ or m_2/m_1
8	TV Cas	A0	7.0 - 7.9	1.8126	70	60	0.128
73	RY Per	B4 + gF5	8.5 - 10.3	6.8636	280	64	0.015
-	IZ Per	B5 (?)	8.0 - 9.2	3.6877	185	37	-
139	RZ Eri	A1m (?) + G8	8.0 - 9.2	39.2807	45	1.8	0.06
426	TW Dra	A6 + G5	7.5 - 9.8	2.8067	50	34	0.0744
453	W UMi	A3	8.5 - 9.6	1.7011	75	61	0.11
563	Z Vul	B3, 4 V + A2, 3 IV	7.9 - 9.3	2.4549	195	103	$m_2/m_1 = 0.42$
578	V505 Sgt	A1 V + F6	6.5 - 7.7	1.1829	102	91	0.137
589 ^b	V477 Cyg	A3 + F5	8.5 - 9.4	2.3470	40	44	$m_2/m_1 = 0.7$
625	W Del	A0e + gG5	9.5 - 12.5	4.8060	30	22	0.013
637	S Equ	B8 V	8.2 - 10.1	3.4360	52	36	0.0043
664	EK Cep	A0	8.0 - 9.4	4.4277	<20	24	0.160
671	AW Peg	A5e + F5 IV	7.5 - 8.2	10.6225	120	9.7	$m_2/m_1 = 0.16$
677 ^b	CM Lac	A2	8.1 - 9.1	1.6047	55	44	$m_2/m_1 = 0.75$
722	Y Psc	A3 + K0	9.0 - 12.0	3.7659	37	27	0.019
725	XX Cep	A8	8.5 - 9.6	2.3373	47	34	0.005

^a The first column gives the number of the system in the 'Sixth Catalogue of Orbital Elements of Spectroscopic Binaries' (Batten, 1967). The last column lists the mass ratio or the mass function.
^b Detached.

TABLE Ib
Semi-detached systems for which rotational velocities of primaries were found in the literature^a

No. in SB catalogue	Name	Spectrum	m_V	Period (days)	v (km/sec)	v_{syn}	$f(m)$ or m_2/m_1
28	U Cep	B8	7.0 - 9.8	2.4929	200-300	100	0.16
75	RZ Cas	A2	6.0 - 7.7	1.1953	82	63	0.023
84	β Per	B8	2.0 - 3.3	2.8673	65	50	0.0255
84	β Per	B8	2.0 - 3.3	2.8673	50 ^b	50	0.0255
111	λ Tau	B3 V + A4 IV	3.4 - 3.9	3.9529	75	77	0.075
409	δ Lib	A0 V + sgG	4.9 - 5.9	2.3273	78	76	0.115
465	AI Dra	A0 + G2	7.0 - 8.1	1.1988	99	86	0.099
513	RZ Scuti	B2	7.5 - 8.7	15.1902	250	18	0.0766
513	RZ Scuti	B2	7.5 - 8.7	15.1902	240 ^b	18	0.0766
557	RS Vul	B5 + G	7.0 - 8.0	4.4773	90	46	$m_2/m_1 = 0.31$
559	U Sge	B9n + gG2	6.5 - 10.1	3.3862	76	88	0.119

^a The first column gives the number of the system in the 'Sixth Catalogue of Orbital Elements of Spectroscopic Binaries' (Batten, 1967). The last column lists the mass ratio or the mass function.

^b As determined in this investigation

to the fraction of the lifetime of an Algol-type s-d system (after the mass exchange stage) during which its primary rotates synchronously.

Inspection of the literature showed us that for only nine s-d systems are accurate rotational velocities, determined from spectra with dispersions of about 20 Å/mm or better, available. The data for these systems are given in Table Ib. The rotation of Algol was determined by Slettebak (1954); the values for U Cephei and RZ Scuti were taken from the above mentioned sources: the data for the six other stars were given by Olson (1968). Since this sample is rather small it was decided to study the rotation of the 16 systems in Table Ia. Apart from the systems already studied by others, these are practically all Algol-type systems in the 'Sixth Catalogue of Orbital Elements of Spectroscopic Binaries' (Batten, 1967) brighter than 9^m.5 at maximum and accessible at Lick Observatory during the late spring and early summer. It was later found that the systems of CM Lac and V477 Cyg are not s-d, hence 14 s-d systems in our sample remain.

Of each system, as well as of Algol and RZ Scuti, at least two spectra were obtained. We used the 20" Schmidt camera of the coudé spectrograph of the 120" telescope, with a dispersion of 16 Å/mm at 4300 Å. The widening used in general was 0.5 mm, although some plates were taken with 0.35 mm widening. In addition spectra of 20 bright A and B stars with known rotational velocities (Slettebak, 1949, 1954, 1955) were taken, which served as standards. All spectra were taken on baked Kodak IIa-O plates. Direct intensity tracing was made of all plates. For the determinations of the rotational velocities the line Mg_{II} 4481 Å was used for spectral types later than B8. For spectral type B8 and earlier the line He I 4026 Å was used. For spectral type B8 both lines were used. The rotational velocities were determined in a way somewhat similar to the one used by Abt and Jewsbury (1969), viz. curves of $v \sin i$ vs. halfwidth and central depth of the standard lines were constructed for the standard stars. The calibration of the halfwidth of Mg_{II} 4481 against Slettebak's rotational velocities indicates a p.e. per star of about 10% in $v \sin i$. The central depth gives a less well defined relation, with a p.e. about twice as large. Measurements of the halfwidth and central depth of the standard lines in the spectra of the Algol-type systems then give 2 values of $v \sin i$. Thirdly, direct visual comparisons were made between the line profiles for the standard stars and the program stars, from which another value of $v \sin i$ was obtained. A similar procedure was followed with respect to the He I 4026 line. Here the p.e. of the $v \sin i$ values derived from the halfwidth relation is about 15%, and of the central depth relation about 20%.

The finally adopted rotational velocity for each star is the average of the 6 values obtained from the 2 plates per star; in determining this average, the values obtained from the central depth were given half weight only.

From the scatter in the 6 values of $v \sin i$ for each star we estimate the internal p.e. in the final average to be about $\pm 10\%$. Table I lists the finally adopted values of the rotational velocity v ; the inclinations i were taken from the best available orbital studies. The table furthermore lists the velocity v_{syn} expected in the case of synchronism. For the computation of this velocity we used the best available determination

TABLE II

The spectral type vs. radius relation adopted for systems for which no accurate radius determinations were available

Spectral type	Radius (in R_{\odot})
A5	1.87
A3	1.92
A0	2.00
B8	2.50
B5-6	3.3
B4-5	4.0
B3	4.7
B2	5.2

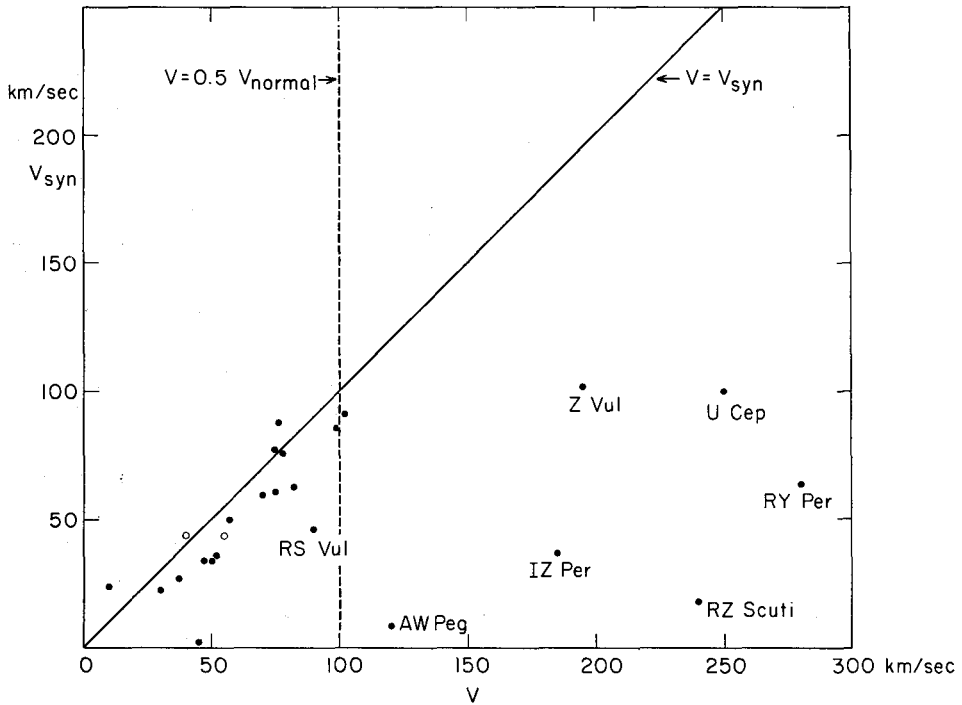


Fig. 1. Plot of the rotational velocities v of primaries of the Algol-type systems from Table I against the velocities v_{syn} expected in case of synchronism between rotation and revolution. Filled circles represent semi-detached systems; open circles indicate the 2 detached systems.

of the radius from photometric and spectroscopic investigations. In cases in which no value for the radius was available we used the main-sequence relation for radius vs. spectral type given by Harris *et al.* (1963) as specified in Table II.

In Figure 1 v is plotted vs. v_{syn} . The non-semi-detached systems are indicated by open circles. The figure and the table show that within the observational uncertainties,

in about 67% of all cases rotation and revolution in s-d systems are synchronised. There seems to be a slight tendency to rotate about 10 km/sec faster than synchronous, although it is not certain whether this is a real effect. It is interesting to notice that all non-synchronous primaries in systems with $P < 5$ days have spectral type B8 or earlier. Systems with $P < 5$ days and primaries of spectral type B8 or later show synchronous rotation in 14 out of 15 cases. The systems RZ Eri and AW Peg, which both have $P > 10$ days, have primaries which still rotate much more slowly than single A-or B-type main-sequence stars. The table shows that the mean rotational velocity of primaries of type B8 or later in s-d systems is about 75 km/sec, which is about 40% of the average value for single late B and early A stars.

Contrary to what is observed for spectral type B8 and later, the primaries of type earlier than B8 rotate on the average more than twice as fast as expected in case of synchronism. λ Tauri is the only synchronous rotator in this group of 6.

These results seem to indicate that in systems with primaries of spectral type B8 or later, and with periods less than 5 days, synchronism is restored quite rapidly after the mass exchange stage, whereas in systems with earlier type primaries resynchronisation might take more than three quarters of the lifetime of the system, after the stage of mass exchange.

The interpretation of this difference in rotational behaviour may perhaps be found in the way in which these systems were produced. For the types of evolution of close binary systems we will use here the notation by Kippenhahn and Weigert (1967), viz.: case A for evolution in which the primary already fills its Roche lobe before the end of core hydrogen burning, case B for the evolution in which the primary fills the Roche lobe after the end of core hydrogen burning but before the onset of helium burning. From the work of Kippenhahn *et al.* (1967) and of Refsdal and Weigert (1969) it is known that Algol-type s-d systems can be produced either by case B evolution with initial primary mass smaller than about $2.8 M_{\odot}$, or by case A evolution for any value of the initial primary mass. The primary masses of the Algol-type systems produced in case B are not expected to be much larger than $4 M_{\odot}$; for an average initial mass ratio of primary and secondary of 2.0, and an initial primary mass of $2.8 M_{\odot}$, the mass of the new primary after the mass exchange is expected to be about $3.8 M_{\odot}$ (cf. Kippenhahn *et al.*, 1967), which is about the mass of a B8 main-sequence star. For this reason, Algol-type systems produced by evolution according to case B are expected to have in general only primaries of spectral type B8 or later.

On the other hand, although case A can in principle occur for any spectral type, it is most common among stars earlier than about B8, as Table III shows. The left-hand side of this table shows the distribution of periods of unevolved B-type spectroscopic binaries as given in the Sixth Catalogue (Batten, 1967); the right-hand side of the table shows the limiting periods $P_{\max H}$ and $P_{\max He}$ defined as follows. In systems with $P < P_{\max H}$ the primary already fills the Roche lobe before the end of core hydrogen burning; in systems with $P < P_{\max He}$ it fills the Roche lobe before the onset of core helium burning. Consequently, systems with $P < P_{\max H}$ are in case A, and systems with $P_{\max H} \leq P < P_{\max He}$ are in case B. Comparison of the left- and right-hand side of

TABLE III

Left: the distribution of periods of unevolved B-type spectroscopic binaries in the 'Sixth Catalogue of Orbital Elements of Spectroscopic Binaries' (Batten 1967). Right: the periods $P_{\max H}$ and $P_{\max He}$ (defined in the text) for three stellar masses, for an original mass ratio of secondary and primary of 0.5.

P (days)	B0-B5	B6-B9.5	M	$P_{\max H}$	$P_{\max He}$
< 1	0.9%	2.6%			
1-1.5	7.9	7.9	$3M_{\odot}$ (\sim B8)	0 ^d .99	35 ^d .4
1.5-2	9.6	7.9			
2-3	21.1	15.8			
3-9	28.9	31.6	$5M_{\odot}$ (\sim B5)	1 ^d .36	92 ^d .2
9-27	17.6	21.0			
27-81	7.0	7.9	$9M_{\odot}$ (\sim B2)	2 ^d .00	406 ^d .4
> 81	7.0	5.3			

Table III shows that case A occurs among about 18% of the early B stars, but among less than 10% of the later B systems. In view of the decrease of $P_{\max H}$ with stellar mass, it occurs among only a few per cent of the A stars (which have about the same period distribution for spectroscopic binaries as the later B stars). For this reason, case A is quite common among unevolved spectroscopic binaries of spectral type earlier than about B8, but is quite rare at later types. For this reason one expects most of the s-d systems with primaries of spectral type B8 or later to be the products of case B evolution, whereas systems with primaries of spectral type earlier than about B8 are expected to be mostly the products of case A.

Why then do the products of case A evolution rotate much faster than the products of case B evolution? The reason might be that in case B most of the mass-exchange takes place in a relatively short time, and there is in general no long lasting stage of slow but considerable mass exchange (Kippenhahn *et al.*, 1967; Refsdal and Weigert, 1969). In this case, therefore, once the mass exchange is over, tidal forces can start their synchronising work. On the other hand, in case A only a relatively small amount of mass is transferred rapidly, followed by a long-lasting stage of slow mass exchange (Plavec *et al.*, 1968). Hence, in this case the surface layers of the primary always consist of newly accreted material, presumably of high angular momentum, which did not yet have time to adjust itself to synchronism. We suggest that this may be the reason for the different rotational behaviour of systems with primaries of spectral type earlier and later than about B8.

One may wonder what will happen to the systems with primaries of spectral type later than about B8, after the subgiant component has evolved into a white dwarf. According to the work of Kippenhahn *et al.* (1967) and of Refsdal and Weigert (1969) the subgiant has a lifetime of only about 15 to 20% of the remaining lifetime of the primary. One therefore expects this main-sequence primary to have a white dwarf companion during 80% or more of its lifetime after the mass exchange. From the fact that, after due allowance for inclination effects, some 2.5% of the A and B stars are

primaries in Algol-type s-d systems (Van den Heuvel, 1969a) one expects some 10–12.5% of the A and B stars to have been primaries in s-d systems, and to have a white dwarf companion now. The fact that for spectral type later than about B8 the primaries of Algol-type s-d systems are slow rotators indicates then, that one expects the 10–12.5% of the late B and A stars which have white dwarf companions, to be relatively slow rotators. This might be the explanation for the observed occurrence of an overabundance of slow rotators among the early A stars (Conti, 1965; Deutsch 1967). Similarly, one expects those blue stragglers in galactic clusters that are evolved spectroscopic binaries to have rotational velocities comparable to those of the stars in Table I. Indeed the A-type blue stragglers in M67 studied by Deutsch (1966) have rotational velocities not larger than about 100 km/sec and the blue straggler 40 Cancri in Praesepe is a very slow rotator (Conti *et al.*, 1965). (The position of the blue straggler 68 Tauri in the colour magnitude diagram of the Hyades can be explained by ordinary evolution of a single star (Van den Heuvel, 1969b).)

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Discussion

Abt: What periods would you expect for the evolved binaries with white dwarf companions?

Van den Heuvel: About the same as or slightly larger than those of Algol-type semi-detached systems. There is a selection effect which favours detection of Algol-systems with short periods. Due to this effect the systems with a white dwarf component may well have larger average periods than the average period of the Algol-type systems in Table I. The expected percentage of the remnants of Algol-type systems given here is therefore also probably an underestimate.

I would further like to stress that the mass ratios of the systems with white dwarfs are very small, and the binary character of such systems may easily escape detection.