PART III

STELLAR ROTATION IN BINARIES, CLUSTERS, AND SPECIAL OBJECTS. STATISTICS OF STELLAR ROTATION

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ROTATION IN CLOSE BINARIES

(Review Paper)

MIROSLAV PLAVEC
Astronomical Institute, Ondřejov, Czechoslovakia

(Paper read by E. P. J. van den Heuvel)

1. Introduction

When studying the axial rotation of the components of binary systems, we ask the following fundamental question: How much is axial rotation affected by the other star? In particular, is there any synchronism between the periods of axial rotation and orbital revolution?

Thus in fact we are more interested here in the angular than in the linear velocity of rotation. It was pointed out by McNally (1965) that the angular velocity of rotation reaches its maximum near A5 and drops off rather rapidly on both sides so that the G0V and O5V stars have approximately the same average period of rotation. The accompanying Table I is an adaptation of McNally's figures.

In the last column of Table I, the orbital period of a binary is given in which both

TABLE I
Average rotational velocities of main-sequence stars

Spectrum (class V)	m ($m_\odot$)	R ($R_\odot$)	V_r (km/sec)	ω_r (10^{-5} sec^{-1})	P (days)	P_c (days)
O5	39.5	17.2	190	1.5	4.85	4.0
B0	17	7.6	200	3.8	1.91	1.75
B5	7	4.0	210	7.6	0.96	1.07
A0	3.6	2.6	190	10	0.73	0.78
A5	2.2	1.7	160	13	0.56	0.53
F0	1.75	1.3	95	10	0.73	0.40
F5	1.4	1.2	25	3.0	2.42	0.39
G0	1.05	1.04	12	1.6	4.55	0.36

components have equal mass (corresponding to spectral type in the first column) and are in contact (more exactly, both fill the critical Roche lobe). This is in fact the shortest possible period in each case; if the companion is less massive and/or more distant, the period will be longer. It is interesting to note that up to the late A's, the average period of axial rotation of single stars and the 'contact' period of revolution given here are about equal. Only for the F dwarfs and later types can we have the orbital period much shorter than the period of rotation.

2. Observational Material

It is clear that the problem of synchronism appears when we deal with close binaries,

A. Slettebak (ed.), Stellar Rotation, 133–146. *All Rights Reserved*

since only in these can a real physical interaction between the components be expected. In visual binaries, the components can be expected to evolve as well as to rotate as single stars. Investigations by Struve and Franklin (1955) and by Slettebak (1963) confirm this expectation.

A statistical study of the problem of synchronism was published by Plaut (1959). His statistics are based on the well-known surveys by Huang, by Slettebak, and by Slettebak and Howard. These data, of course, refer to the linear velocities of rotation. Therefore it is necessary to know the star's radius in order to compute the corresponding synchronised linear velocity. Plaut derived the stellar radii from photometric elements for eclipsing binaries, and from absolute magnitudes and spectral types for spectroscopic binaries.

Plaut concludes that the periods of rotation and revolution seem to be equal on the average for orbital periods shorter than 10 days, while for longer periods the synchronisation fails and the stars tend to rotate rather like single stars. However, Plaut's diagram shows a very large scatter. This is certainly partly due to the unknown value of orbital inclination i, which enters as $\sin i$ into the observed velocity but does not enter into the computed value of the 'synchronised' velocity $v_s = 2\pi R/P$. Large observational errors affecting R are another source of scatter. Apart from this, we should realize that orbital period alone cannot characterize the binary uniquely. A pair of O stars revolving with a period of 10 days can easily be understood to have synchronized rotation because the two bodies are almost in contact; while the same period in the case of two G dwarfs means that their radii represent only 0.07 of their separation, and interaction is certainly much weaker.

Practically only well-observed eclipsing binaries can yield complete data for a more detailed investigation into the problem of synchronism. Here we can get not only the radii of the stars but also the orbital inclination if we take it for granted that the axes of rotation are perpendicular to the orbital plane. Unfortunately, strong selection effects restrict our considerations almost entirely to periods of the order of a few days, and no statistically meaningful information can be obtained at this time about the systems with period one or two orders of magnitude longer.

The present discussion will be based mainly on two papers, by Koch *et al.* (1965) containing the rotational velocities of 19 eclipsing pairs, and by Olson (1968) who added another 9. Figures 1 to 4 are similar to those displayed in the original papers. I have added three stars studied by other authors: α CrB, RZ Sct, and RY Per. All three are exceptions rather than ordinary cases because of their rapid rotation, and are marked specifically in the figures.

Another change introduced here is the distinction between detached binary systems (circles) and semidetached ones (squares). This is because these two categories of close binaries are very likely to have different life histories. In the detached systems, both stars lie on or near the main sequence, and they are significantly smaller than their corresponding critical Roche lobes. In the semi-detached systems, only the more massive primary is a main-sequence star, while the less massive and colder secondary is a subgiant or giant, i.e. apparently more evolved. This paradox is in my opinion correctly explained as a consequence of a large-scale mass transfer in which the originally more massive star lost a considerable part of its mass and developed into the subgiant secondary (cf. Plavec, 1968a, b).

3. Observational Evidence on Rotation in Close Binaries

In Figure 1, the linear velocities of rotation of the components of close binaries are plotted against their respective spectral types. Primary components are marked by full symbols, secondary components with open symbols. The broken full line represents the mean velocities of rotation for single class V stars after Slettebak (1963). In

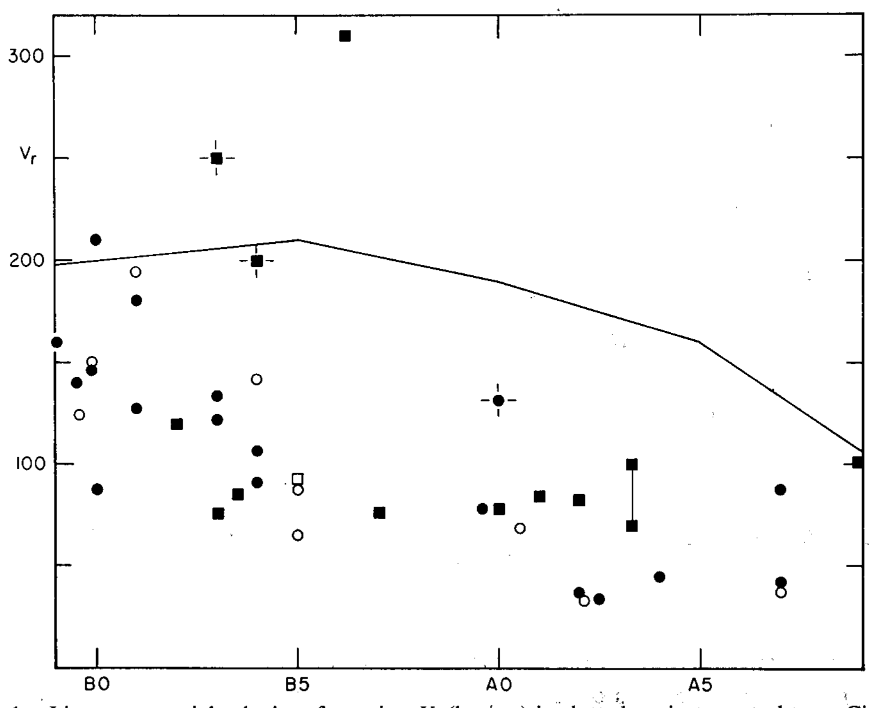

Fig. 1. Linear equatorial velocity of rotation V_r (km/sec) is plotted against spectral type. Circles: detached systems, squares: semidetached systems. Open symbols: secondary (less massive) components, full symbols: primary components.

agreement with Koch *et al.*, and with Olson, we find a definite tendency of the components of close binaries to rotate more slowly than is the average for single stars of the same spectral class. Thus the influence of the other component is certainly perceptible.

Figure 2 compares the actual velocity of rotation V_r with the calculated synchronized velocity V_s. In the case of perfect synchronism, the stars should lie on the 45° line. Disregarding the very few striking deviations for the moment, we find that most

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of the stars do scatter along this line, indicating that synchronization obtains in most cases either perfectly or approximately.

It is difficult to say how much of the scatter in Figure 2 is real. Certainly observational errors play an important role, as is shown by the following examples. Three

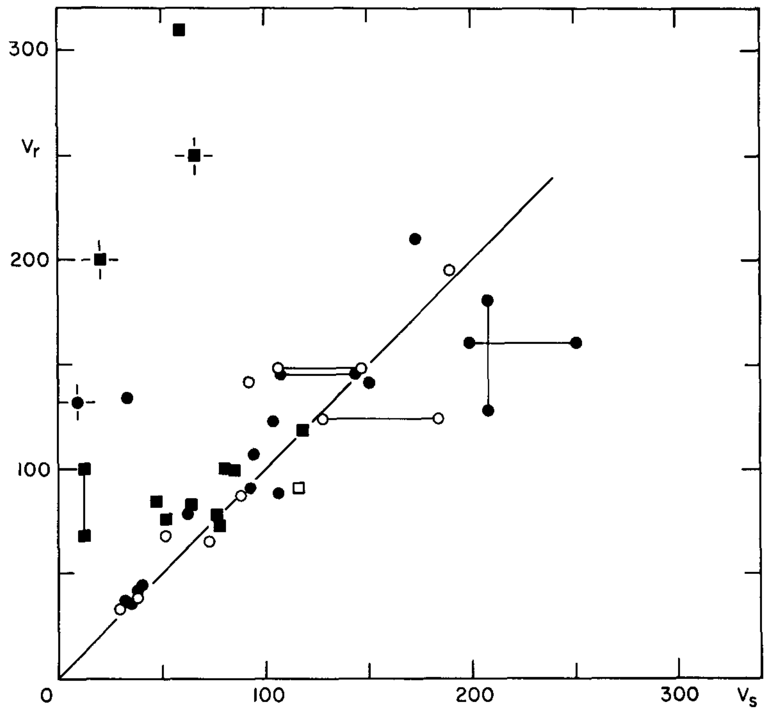

Fig. 2. Observed linear velocity of rotation V_r is plotted against the 'synchronized' velocity V_s, both in km/sec.

stars lie apparently considerably below the line of synchronism: the primary of VV Ori, and both components of AO Cas. The synchronized velocity for VV Ori would be 208 km/sec, while Olson found the actual velocity to be 128 km/sec. A causal inspection of a few of the Victoria plates shows that the lines are very poorly defined. One would expect a higher velocity of rotation, and indeed Boyarchuk and Kopylov (1964) list a value of 180 km/sec. If something like this is more correct, then the discrepancy will be greatly diminished (cf. the point on the top of the vertical line in Figure 2). In AO Cas, the radii of both stars are quite uncertain, since the absolute dimensions are uncertain. In fact, Koch *et al.* found rather widely different values for the radii according to whether they computed them from the photometric elements or from the radiation law. The difference is shown by the two horizontal and parallel lines below the 45° line. In some cases the disagreement between the two solutions for the stellar radius is rather alarming. In AO Cas, the photometric solution gives much better agreement between V_r and V_s, but for Y Cyg (the two horizontal lines very close together above the $V_r = V_s$ line) just the opposite is true.

These examples show that not much weight can be placed on the accurate position of the points in Figure 2. Nevertheless, since the errors are probably at random, we may conclude the following: (1) No case is known of a component rotating considerably more slowly than required by synchronism. (2) As a rule, the rotation is synchronized with orbital motion, or may be somewhat faster. (3) A few stars rotate considerably more rapidly than they should if synchronism applied to them.

Among the non-conformists, there are two components of detached systems. The primary of α CrB should rotate at 9 km/sec if synchronism applied to it, but it rotates 14 times faster, at 132 km/sec which, however, is still considerably less than average for an A0V star. With a period of 17.4 days, and a companion of less than a solar mass, this deviation from synchronism is not surprising.

The other star is the primary of AR Cas which has a period of 6.1 days and a mass ratio probably even smaller than α CrB. Thus the influence of the companion will probably be weak, too. The expected synchronized velocity is 32 km/sec, while Olson observed 134 km/sec. Even this is considerably less than average for a B3V star. However, Batten (1961) reports that the rotational effect within eclipse indicates a velocity of 210 km/sec$\pm$50 km/sec; the upper half of this range would be a value rather typical for a single B3V star.

These two cases would indicate that synchronism breaks down at fairly short periods already. But the two other cases – admittedly less reliable – of δ Ori (5.7 days) and V 380 Cyg (12.4 days) indicate good synchronization. Figure 4 shows that in fact nothing statistically meaningful can be said about periods longer than 4 days!

As has already been said in connection with Plaut's diagram, orbital period alone is certainly not sufficient to determine the degree of interaction between components. One could expect that the synchronizing effect of the companion will increase with the fractional radius of the perturbed star; but Figure 3 yields no clear support to this contention.

4. Tidal Forces

In spite of the rather unsatisfactory supporting evidence from Figure 3, the classical tidal forces must be considered seriously in an attempt to explain the general trend towards synchronism. The problem was discussed recently by Huang (1966). He refers to the result obtained by Cowling (1938) that the time of adjustment of a star to an external gravitational field is of the order of the period of free adiabatic oscillations, which is as a rule much shorter than the orbital period. Thus the shape of the star is almost instantaneously adjusted to the perturbing gravitational field. Huang concludes: "As a result the two stars will have their longest axis along the line joining their centers, and the components, always facing each other, will rotate in synchronism with their orbital motion" (*ibid.* p. 50).

However, in the latter part of this sentence Huang was misled to a conclusion not warranted by Cowling's reasoning. It is true that if an external potential is applied to

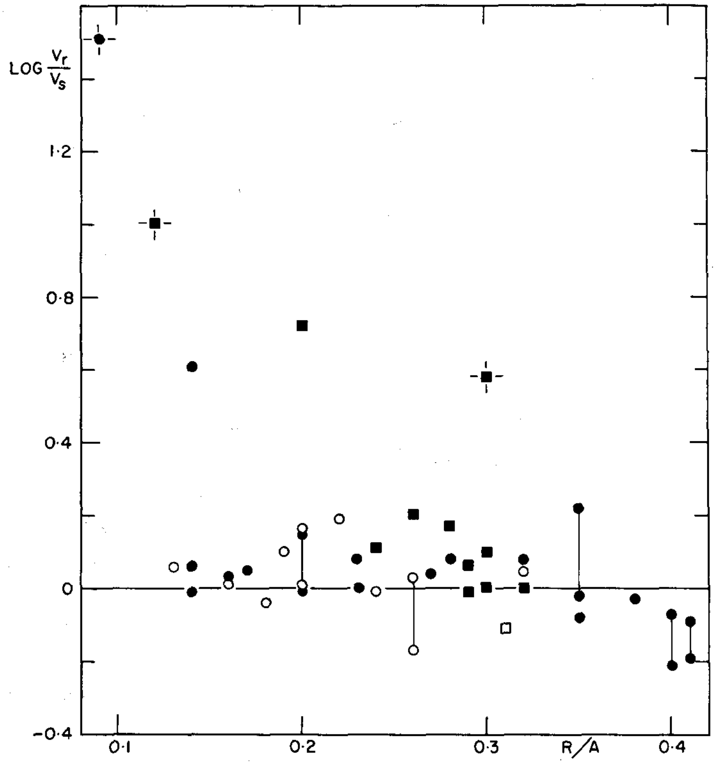

Fig. 3. Departures from synchronism are plotted against fractional radii R/A. Zero line corresponds to synchronism.

a star, it settles down to a hydrodynamical equilibrium in a very short time (of the order of the free-fall time). Thus its shape is almost instantaneously adjusted to the external field, but this does not imply that the rotation will adjust itself as well. If there were no friction or dissipation of energy, the star would rotate indefinitely at any given speed. A change in rotation requires a change of angular momentum, and for this a torque is needed. There is, however, no torque unless there is some friction inside the body of the star. The formula for the torque is

$$\Gamma = -\int \frac{\partial U}{\partial \varphi}\, \varrho \, \mathrm{d}V \tag{1}$$

where U is the external potential, φ is the azimuthal angle, and ϱ is the local density within an elementary volume $\mathrm{d}V$. When ϱ has the same spatial symmetry as U, the net torque is zero. But the potential is as a rule variable with time, and causes oscillations in the density distribution inside the star. These oscillations are not exactly in phase with the perturbing potential, the phase lag being due to friction. It is just this little phase lag that makes the net torque non-zero, and causes secular exchange of rotational and orbital angular momenta. These dissipative tides are very much smaller

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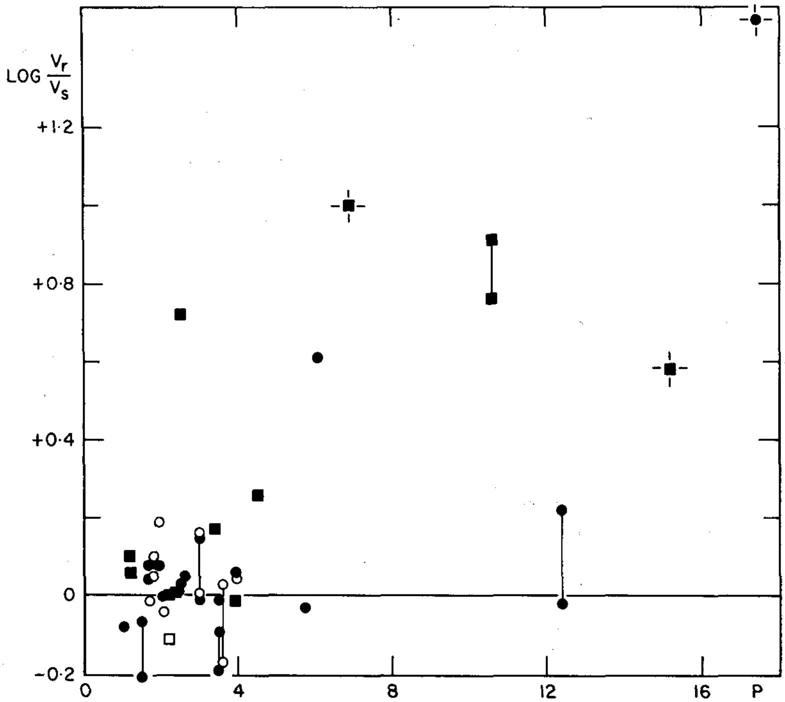

Fig. 4. Departures from synchronism are plotted against orbital period P (in days).

than the adiabatic tides that are exactly in phase with the perturbing potential and tend to adjust the shape of the star instantaneously to the external field of force. Therefore the adjustment of rotation to the condition of synchronism is a much slower process than the adjustment of the star's shape.

Recent years have witnessed a substantial revival of interest in the theory of tidal forces in the works by Kopal (1968), James (1967), Dziembowski (1967) and Zahn (1966). The following discussion is based mainly on the comprehensive work by Zahn.

The tidal effects are relatively large if the perturbed star has an extended outer convective zone, since the eddy viscosity is fairly large. Zahn finds that in this case the deviation of the actual angular velocity of rotation ω from the synchronized value ω_s decreases exponentially with time:

$$\omega - \omega_s = (\omega_0 - \omega_s)\exp(-t/\tau_c) \tag{2}$$

where the characteristic time constant τ_c can be taken as

$$\tau_c = QC_cP^4 \tag{3}$$

with

$$Q = \tfrac{4}{9}(1+q)^2, \tag{4}$$

where P is the orbital period in days, and $q = m_1/m_2$ is the mass ratio, m_1 being the perturbed star. C_c is a constant depending entirely upon the internal constitution of the perturbed star. For main-sequence stars with an extended outer convective zone, i.e. for late-type dwarfs less massive than the sun, Zahn finds a value of the order of 10^{-1} to 10^{+1} years. Among the spectroscopic binaries, red dwarfs may occur as secondaries in detached systems. Since Q will not be far from 1 in these cases, the characteristic time constant for a system with $P=10$ days is of the order of 10^3 to 10^5 years, i.e. quite short compared with the main-sequence lifetime of these dwarfs. Thus in spectroscopic binaries of short or moderate period, the secondary components if less massive than the sun can always be expected to rotate in synchronism with orbital motion.

But this result does not solve the problem of our statistics, since there is not a single star of this kind in Figures 1 to 4. Typical stars in our sample are main-sequence stars more massive than the sun, possessing a small convective core and an outer radiative envelope. Now the radiative viscosity due to radiative damping is incomparably smaller than the turbulent viscosity. Therefore the radiative tides are extremely inefficient and their time scale is of the same order as the main-sequence lifetime of the star in question, if not longer.

In other words, it seems that the observed good degree of synchronism can actually not be explained as easily as one might think. If further investigations on more up-to-date stellar models confirm that the tidal forces do not provide an adequate explanation, I suggest that we could think of three possible ways out of this dilemma:

(1) We could perhaps preserve the tidal forces but assume that the most important evolutionary phase determining the angular momenta is the one preceding the main-sequence phase. During the initial contraction, a large-scale convection in stars of large size, and quite possibly also exchange of material, may fix the rotational velocities near the synchronised values. This would explain why synchronism is observed in such a young system as AG Per which appears to be a member of the II Persei association whose kinematic age is about 1.6×10^6 years. Moreover, it may well be that the very early stages of evolution of a binary determine the important circumstance that the axes of rotation are perpendicular to the orbital plane – if, of course, this is really a fact and not merely our oversimplified assumption!

If we make the assumption that the two components rotated in synchronism at a stage shortly preceding the main-sequence stage, we may perhaps argue that the final stages of (already rather slow) contraction lead to a slight increase in the velocity of rotation above the synchronized value, which appears to be the rule with main-sequence systems.

(2) Alternatively, perceptible changes of angular momenta on a relatively short time scale in the course of the main-sequence evolution of the components are perhaps possible if we admit that more powerful forces than the radiative tides may be at play. Dziembowski points out that the action of the Coriolis force on meridional circulation may be perceptible on a time scale considerably shorter than that of the radiative tides. What we need is a more detailed theoretical inquiry into these problems which should bear out whether there would be a trend towards synchronism as well as how efficient these forces are.

(3) As a third possible explanation of the trend towards synchronism, we should realize in any case that what we observe is the rotation of the outermost layers of the star only. If there occurs turbulence in these layers – and there appears to be more than one way of establishing it – the convective tides may create a kind of 'superficial synchronisation' masking the actual state of things underneath.

5. Mass Exchange and Rotation in Binaries

The last item leads rather naturally to another phenomenon which may affect rotation very perceptibly, and this is the mass exchange between components. I think a good argument in favor of this idea is to have a closer look at the most conspicuous deviations from synchronism in Figure 2. Omitting α CrB and AR Cas, we are left only with semidetached binaries, namely (from left to right) AW Peg, RY Per, U Cep, and RZ Sct; all of which are the primary components. Other primaries of this type, too, show a trend toward faster rotation than synchronism requires. Although in their case the deviations are not so striking, they seem to be well established; I have in mind in particular U Sge ($V_r/V_s=1.5$), RS Vul (1.8), and RZ Cas (1.3).

Now it has already been mentioned that the best explanation for the existence of the semidetached systems is a large-scale mass exchange that starts when the more massive star reaches, in the course of its secular expansion, the limit of dynamical stability (the Roche limit). The material driven beyond this limit leaves the star very quickly and most of it is probably captured by the other component. The mass-losing star strives to adjust its structure, and in particular its radius, to this new condition of lower mass. The new equilibrium radius is as a rule smaller than the initial one, although this need not always be the case. But in practically all cases the equilibrium radius is larger than the new Roche radius, since the latter decreases more quickly with diminishing mass of the star in question and with increasing mass of the other component. As a consequence the mass-losing star cannot reach its equilibrium radius, since a smaller radius is forced upon it by external forces. Therefore the mass loss goes on and the process is in fact self-accelerating for some time as the star's deviation from thermal equilibrium increases.

Our model calculations were made on the assumption that the total mass and total orbital angular momentum of the binary system remain preserved – in other words, that the material is only being exchanged but does not escape from the system. If so, then it can easily be shown that the distance between components attains its minimum when both stars have equal mass, and approximately at the same time the Roche radius of the mass-losing star reaches a minimum, too. From now on, further mass loss is bound to increase the star's actual radius, because the dimensions of the system increase again. As a consequence, the deviation from thermal equilibrium diminishes steadily until the moment comes when the star's actual radius (as given by the instantaneous Roche radius) equals the equilibrium radius, so that thermal equilibrium is restored. From now on, the initial primary in fact continues its interrupted evolution on the nuclear time scale. Its mass has been reduced considerably (it is now the less massive component), and its internal constitution has been adjusted to this present condition. This does not mean that the star is similar to a main-sequence star of the same mass. What has changed is not only the total mass but also, for example, the mean molecular weight. As a consequence, the star is a subgiant overluminous for its mass. But its constitution has undergone no fundamental change: it still possesses a convective core in which hydrogen is being converted into helium. In fact, the hydrogen content within this core remains almost unchanged over the period of the rapid mass exchange described above, since the process is quite fast – its duration is of the order of 10^{-2} of the total main-sequence lifetime of a single star of the same initial mass.

As the hydrogen burning in the core continues, the star's envelope expands slowly. But the star filled its critical Roche lobe to begin with. Therefore the mass loss continues, but this time much more slowly and on a nuclear time scale. The mass-losing star is now the less massive one, and the absolute size of its critical Roche lobe now increases with decreasing mass, because with increasing disparity between the components their separation is bound to increase rapidly if the total angular momentum is to be conserved. Therefore the star balances always very near thermal equilibrium. This phase of slow mass loss usually lasts very long and may well have a duration comparable to the main-sequence lifetime of a single star with the same mass as the mass-losing star initially had. Since, moreover, the system can produce very deep eclipses if the orbital inclination is favorable, the probability is comparatively high that the binary will be observed just at this stage of evolution. We believe that most if not all Algol-like semidetached binaries are observed at the stage of slow mass loss. The chance of catching a system at the phase of rapid mass loss is low because of the short duration of that phase, but of course it is not negligible since the spectroscopic phenomena that may accompany this process may be quite conspicuous.

For our considerations about how this process can affect the axial rotation of the components it is necessary to have at least some quantitative picture of the process of mass exchange. No unique figures can be given since the rate of mass exchange depends on several parameters, in particular on the masses, mass ratio and on the degree of chemical inhomogeneity of the mass-losing star. For moderate masses and mass ratios, the case with the following initial conditions may be considered as rather representative: $m_1 = 5\, m_\odot$, $m_2 = 3\, m_\odot$, $X_{c1} = 0.25$ (Plavec *et al.*, 1969). At the phase of rapid mass loss, the primary loses and the secondary gains $2.4\, m_\odot$ within 7×10^5 yr, so that the average rate of mass loss is $3.4 \times 10^{-6}\, m_\odot$/yr. The process is, however, not uniform. The outflow is fastest shortly after the beginning, and attains a maximum rate of $2 \times 10^{-5}\, m_\odot$/yr. The star reaches minimum size and luminosity within only 1.2×10^5 yr after the beginning of mass loss. The subsequent phase of partial restoration of luminosity, when the star gradually returns to thermal equilibrium, takes 5.8 $\times 10^5$ yr, and the average rate of mass loss is $2.4 \times 10^{-6}\, m_\odot$/yr. This is still very high compared to the slow phase of mass loss that follows, where the average rate is only $1 \times 10^{-8}\, m_\odot$/yr.

However, owing to the long duration of the latter phase – some 65×10^6 yr in the particular case considered here – the total amount of material transferred is certainly not negligible, amounting as it does to 0.6 $m_\odot$. The corresponding quantity for the fastest phase is 1 $m_\odot$, while the 'intermediate' phase is most efficient with 1.4 $m_\odot$ transferred. All this material is assumed to be captured by the other component. It is this mass-gaining component that is observed as the main-sequence, bright and massive primary in the Algol-like semidetached systems, and its velocity of rotation is usually measured. Now the transfer of material on it certainly affects this star's angular momentum profoundly – but very little can be said about this point at the present.

The truth is that the theory of evolution of close binaries through mass exchange is still very crude. The model computations performed by Kippenhahn, Weigert, Refsdal, Paczynski, by our Ondrejov group etc. have dealt so far exclusively with the mass-losing component. The assumption of conservation of the total orbital angular momentum is partly based on the well-known fact that in all binaries (except the W UMa systems) the angular momenta of axial rotation are small compared to the orbital angular momentum. This very argument when reversed means, however, that the axial angular momentum can be considerably changed by transfer of mass carrying with it a certain amount of orbital angular momentum.

The problem that must be solved can also be formulated as follows: Granted that the mass loss of the initially more massive component proceeds roughly as described above, is the other component capable of accommodating the incoming material on a time scale comparable to that of the mass loss? Observational evidence seems to answer this question in the affirmative, since we observe many Algol-like systems in which the primary behaves as a normal main-sequence star, and its rotation is nearly synchronized.

It can be argued, however, that many of the observed semidetached systems may be rather old, i.e. well advanced in the phase of slow mass loss which can be quite long. The present rate of mass exchange may already be quite low. In fact, in typical systems like U Sagittae, RW Tauri or U Coronae Borealis the process manifests itself only by rather weak spectroscopic phenomena (temporary appearance of emission and/or absorption satellite lines), and by changes of period. Indeed, the intermittent appearance of emissions and the erratic character of the period fluctuations makes one suspect that what we observe here may be atmospheric activity of the subgiant component rather than the continuous secular flow postulated by our theoretical evolutionary models. No secular increase of period has so far been established with certainty (Koch, 1969), which again is no argument against secular mass exchange since our observations cover too short an interval of time.

Whether the cause of the observed mass transfer is secular or superficial instability, there is little doubt that the material is streaming from the subgiant to the main-sequence component, partly falling directly on it and partly encircling it temporarily in the form of a ring. Although this picture is rather simple, we lack quantitative data about the rate of mass transfer. In fact, for our considerations about its effect on rotation we need more than this – namely we must know how the material flows and how it falls on the star. This is certainly a problem of hydrodynamics, and may easily involve magnetohydrodynamics as well if magnetic fields are present. This makes the whole problem almost formidably complex. No wonder, then, that hardly more than the crudest approximation has been attempted – namely the calculation of trajectories of discrete particles in a purely gravitational field.

The immediate aim of these calculations was in fact to explain the gaseous rings circulating around the more massive components in systems like RW Tau, U Sge or U Cep. In our work at Ondrejov (Plavec and Kříž, 1965) we did find certain trajectories that may contribute to a general circulatory pattern around the more massive star. They require a certain area of ejection from the surface of the subgiant, and fairly high initial velocities (over 100 km/sec); therefore some intrinsic force must be postulated in the atmospheres of the subgiants capable of expelling the particles.

If the ejected particles are not properly directed or have lower ejection velocities, they fall directly onto the more massive star. Presumably this is the fate of the major part of the expelled material, and it should fall on rather a limited area of the star's surface. Most of the trajectories tend to lie near the orbital plane, and centrifugal force lifts them ahead of the line joining the two stars. Thus they are in a sense 'focused' to an equatorial area centered around a point located, say, some 50° off the axis of symmetry of the system. The particles arrive with velocities of the order of 500 km/sec, but in general their direction is not normal to the surface, and there exists a finite positive component tangential to the surface and in the direction of axial rotation and orbital motion. The trend is therefore to accelerate the rotational velocity of the main-sequence component.

It may be argued that the discrete-particle approach is too crude. Prendergast (1960) attempted a hydrodynamical approach, although, in order to make the problem tractable, he again oversimplified the gravitational field. His solution describes not the streaming but a steady-state distribution of gas in the system, his main conclusion being that the streaming around the more massive component is essentially Keplerian motion around its center of gravity. The same conclusion was reached by Huang (1966). This means that if there is any interaction between the star and the surrounding gas, or if indeed parts of the gaseous ring mix with the superficial layers of the star, the result must inevitably be an increase of its velocity of rotation.

This result contradicts the conclusion by Van den Heuvel (1968) that the incoming material slows down the star's rotation, which statement he uses to support his contention that the Ap and Am stars (known as slow rotators) are members of close binaries in which mass exchange took place. Strictly speaking, Van den Heuvel did not consider the Algol-like binaries but systems of longer period – but even so I do not think his result is acceptable unless we admit that the motion of the gaseous masses is largely governed by a strong bipolar magnetic field. Of this we have no indication whatsoever in the Algol-like systems.

The root of the difference between Van den Heuvel's approach and ours is that he assumes that near the surface of the mass-gaining component, the gaseous particles move in roughly circular orbits with an angular velocity equal to the synchronized angular velocity of the system. In a field of force where gravity dominates this certainly cannot be so. It is much more appropriate to assume that the field there is determined by the attraction of the mass-gaining component only. Denoting the mean angular velocity in this field and at the surface of the star by ω_r, and the synchronized angular velocity by ω_s, we have for their ratio

$$\omega_r/\omega_s = (A/R)^{3/2}(1/1+q)^{1/2}. \tag{5}$$

In a typical Algol system, the fractional radius of the more massive star $R/A \cong 0.2$, the mass ratio $q = m_2/m_1 \cong 0.3$, so that the ratio $\omega_r/\omega_s \cong 10$.

One should in fact rather wonder why only a small fraction of the observed main-sequence components of the semi-detached Algol-like systems rotates with velocities much in excess of the synchronized velocity. The reason probably is that in most cases the rate of mass exchange is already low, and the excess angular momentum brought to the more massive star by the falling material is small compared to its total angular momentum of axial rotation. Moreover, this excess is probably rather rapidly redistributed throughout the star. We could speculate that the rapid rotators like U Cephei or RZ Scuti are in an evolutionary stage where the rate of mass transfer is higher. For example, we could think that they are in the 'intermediate' phase of mass exchange where the rate is about two orders of magnitude higher. Or, because both represent relatively massive systems, that the rate of mass loss is generally higher in them.

If this idea is correct, then we should realize that in systems in which the rate of mass exchange is very high – in those which are in the 'rapid phase' – the effect of mass exchange on the rotation of the mass-gaining component must be even stronger, and leads perhaps to a formation of transient thick and partly or completely opaque disks or shells, and to rotational velocities that bring the star to the verge of stability. It has already been suggested (Plavec, 1968a) that β Lyrae and V 367 Cygni are at the stage of rapid mass exchange. But I should like to point out that this picture may be of great importance for a whole class of objects, namely for the shell stars – or at least for some among them. It is certainly possible that some of the shell stars create their extended atmosphere by internal forces of a single star. On the other hand the duplicity of 17 Leporis (Cowley, 1967) or AX Monocerotis (Cowley, 1964), and the strongly suspected duplicity of o Andromedae or φ Persei, indicate that duplicity may be essential for the phenomenon. If so, then both the rapid rotation of the star and its shell may be connected with mass exchange in the binary.

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Discussion

Deutsch: I think it hard to believe that only coincidence is responsible for Dr. Plavec's table, which shows that: $\langle P_{\rm rot}\rangle$ and $(P_{\rm orb})_{\rm min}$ are equal between types O and G along the main sequence.

Plavec: I suspect, too, that this is no coincidence – this is why I presented the table. Perhaps this relation has something to do with the formation of double stars.

Olson: I agree with Dr. Plavec that it is difficult to distinguish between binary components that are 'in synchronism' and 'near synchronism'. The radius must be known accurately, and this depends on the quality of the light and radial velocity solutions, which are often complicated by interaction effects. The rotational velocity determination must be as free of systematic error as possible. The systematic error does appear to be small for 68 Her, whose primary eclipse rotational disturbance has been carefully analysed from Kitt Peak coudé spectra by Dr. Koch and Dr. Sobieski (130th meeting of the American Astronomical Society). They found $v \sin i = 118$ km/sec, while from line widths I found (116 ± 4 me) km/sec. My rotational velocity system shows no significant systematic differences from that of Dr. Slettebak for $v \sin i$ less than about 200 km/sec, which is the range of interest for most close binaries.