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ON THE SUBGIANT COMPONENTS OF ECLIPSING BINARY SYSTEMS

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ABSTRACT

A recent paper by Parenago (1950) on the subgiant components of "single-line" eclipsing binary systems of the Algol type has been studied in the light of a result by Struve (1953), showing statistically that the luminosities of the subgiant secondaries depend not only on their masses and radii but on the mass ratio of the components. This mass ratio is directly related to the size of the zero-velocity surface passing through the inner Lagrangian point of the system, which sets an upper limit to the size of the star. From the photometric radii of the secondaries it was possible to obtain an upper limit to their masses. Those with mass limit less than 1 ⊙ were classified as definitely abnormal subgiants. These stars were found to lie, as a group, very near their maximum size. An evolutionary mechanism is proposed, relating the advanced "biological age" of these stars to the fact that they fill the inner zero-velocity surface.

I. INTRODUCTION

It has often been suggested that subgiant stars fall into two physically distinct classes, the first class containing all single stars, whereas members of the second class occur only in close binary systems, as exemplified by eclipsing systems with Algol-type light-curves. Such systems might also include the first or normal type of subgiant, whose prototype is the A component of the visual binary ζ Herculis. Eclipsing binaries are therefore a profitable field of study for clarifying this distinction. P. P. Parenago (1950) has recently listed 82 eclipsing variables for which spectroscopic determinations of the velocity-curve of the primary component alone are available. From these he selected 54 systems that also possess adequate photometric data. One of these systems has a supergiant primary. The remaining 53 all have main-sequence primaries and form the subject matter of this paper. The work of Parenago has recently been reviewed and discussed by Struve and Gould (1954). Struve (1953) has shown statistically that the luminosity of a subgiant secondary depends not only on its mass and radius but also on the mass ratio of the components of the binary system.

By choosing the mass of the primary in each case as the average main-sequence value corresponding to the observed spectral type, Parengo was able, from the spectroscopic and photometric data, to compute directly the mass and radius of the secondary, as well as the distance between the components. A survey of his list shows at once that the masses of the secondaries are, on the average, below the solar mass, while their radii are considerably larger than the sun's radius. Now the size of a star which is a member of a binary system is limited by the dimensions of the zero-velocity surface surrounding it, which passes through the inner Lagrangian point L_1. We shall refer to this as the inner zero-velocity surface. Its dimensions are always smaller for the less massive component. The question arises, then, as to whether in some cases the secondary component (assumed to be the less massive) fills this inner surface, as illustrated schematically in Figure 1.[1]

II. THE GROUP OF ABNORMAL SUBGIANTS

The stars of Parenago's list were therefore plotted on a diagram (Fig. 2) for which the abscissa was r_2 (the photometric radius of the secondary), and the ordinate the ratio μ

[1] In the case of contact binaries, the limiting size is given by the zero-velocity surface passing through the second Lagrangian point, L_2, as in the case of β Lyrae. However, if only one star fills the inner surface, a common envelope cannot exist, and one must take the inner surface as that of the swollen star.

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of the mass of the secondary to the sum of the masses. On this same diagram a theoretical limiting curve was drawn, giving a lower limit to μ for a given r_2. To define this curve, it was necessary to ascertain that dimension of the inner surface which is measured as the photometric radius. For values of μ greater than 0.2, the mean radius of the inner surface as defined by Kuiper (1941, Table 3*c*) was used. This corresponds to the cube root of three radii defined as the distance from the center of the secondary to the surface, taken, respectively, parallel to the rotation axis, along the interstellar axis (x-axis) away from the primary, and perpendicular to these two. For $\mu < 0.2$ the curve was sketched so as to pass through the point $\mu = 0$, $r_2 = 0$. The theoretical curve is therefore quite rough. It could have been improved by making use of the asymptotic behavior of Kuiper's radius for very small μ. However, the exact location of the curve should not be regarded too seriously for several reasons. First, the curve is not really defined, since the photometric radius of the secondary also depends to some extent on the radius of the primary and on the inclination of the orbit, because of distortion from sphericity. Second, and most important, the data (Fig. 2) indicate that abnormal subgiants (see definition

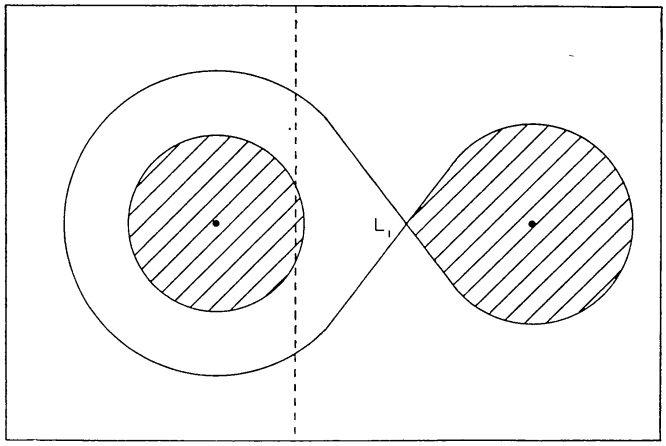


FIG. 1.—Schematic diagram of the zero-velocity surface passing through the inner Lagrangian point L_1, for the case $\mu = 0.25$. Section in xz-plane. Axis of rotation (through center of gravity) shown as broken line. The size of the primary star is drawn arbitrarily.

below) may tend, on the average, to overstep the limiting boundary (perhaps because of the effects of the dynamical equilibrium of the matter lying near the boundary). This indication would, for instance, be accentuated if we had used Wood's (1950) limiting curve, as some subgiants above the curve would cease to be classified as abnormal. It should be emphasized that a quantitative description of these systems is not intended in this paper.

The results of this comparison are shown in Figure 2. It appears that there is a significant separation between the main-sequence secondaries and the subgiant secondaries and, in addition, a tendency for the subgiants to cluster quite near the curve. This suggests that many of the subgiant components do fill the inner surface.

As was mentioned earlier, the position of the points in Figure 2 depends on Parenago's guess as to the mass of the primary. However, the mass function,

$$\frac{\mathfrak{M}_2^3}{(\mathfrak{M}_1+\mathfrak{M}_2)^2} = \mu^2\mathfrak{M}_2,$$

is known from observation (the inclination of the orbit is obtained from the photometric data). Since the secondary cannot lie below the curve, we can, by placing it on the curve

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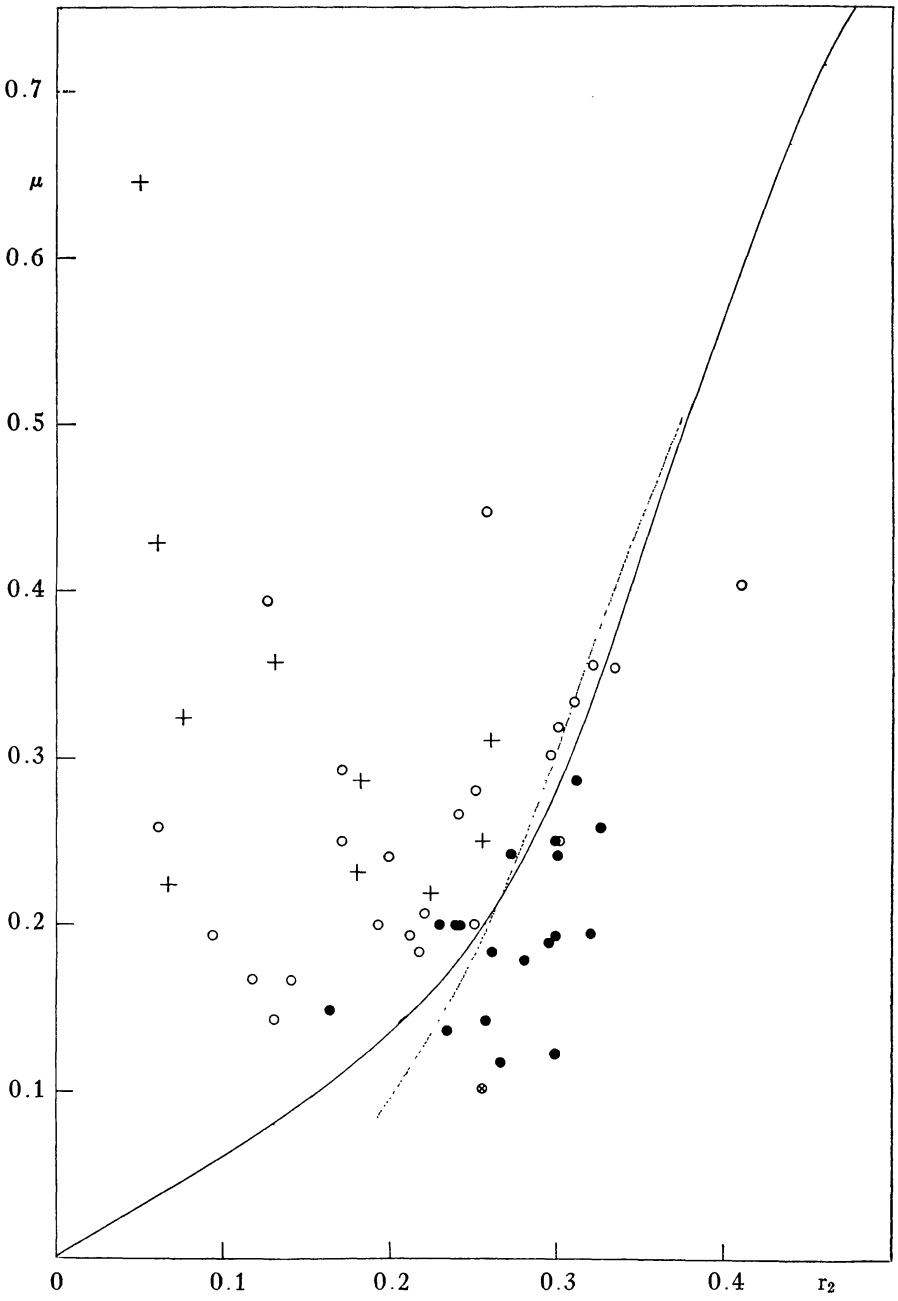


FIG. 2.—The quantity μ is plotted against the photometric radius of the secondary (in units of the semimajor axis of the orbit), r_2, for 53 systems, with the primary on the main sequence. Those with main-sequence secondaries are indicated by crosses. The 18 dots represent subgiant secondaries whose upper mass limit is less than $1\odot$. The open circles are other subgiants. One subdwarf is indicated by a crossed circle. The full curve is the limiting curve as defined in the text. The dotted curve is a limiting curve as defined somewhat differently by F. B. Wood (1950).

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obtain a lower limit $\mu_{\min}$ for μ and an upper limit $\mathfrak{M}_{2\,\max}$ to its mass, given by the following expression:

$$\mathfrak{M}_{2\,\max} = \mathfrak{M}_2 \left(\frac{\mu}{\mu_{\min}}\right)^2.$$

This was done for all 53 secondaries. It was found that 19 stars had an upper mass limit less than one solar mass; 18 of these are classified by Parenago as subgiants and are indicated in Figure 2 as black dots (the remaining secondary is listed as a subdwarf). It is evident that they cluster nearer the curve than do the total group of subgiants.

It therefore appears justifiable to suppose that these 18 secondaries actually do lie on the curve, that is to say, fill the inner zero-velocity surface. On the other hand, these stars were chosen because they form a peculiar group, combining subgiant character with small mass ($<1\,\odot$). It is not possible to understand how stars with such small mass could have had enough time in five billion years to reach the advanced stage of evolution suggested by their subgiant characteristics, unless they had originally a very unusual chemical composition not shared by their companions. In the following section a hypothesis which relates the peculiar properties of these stars to the fact that they fill the inner zero-velocity surface will be discussed. First, however, a word should be said about luminosities. Parenago has obtained average luminosities of secondaries by fixing the absolute magnitude of the primary at the average value for main-sequence stars. The observed difference in magnitude and a bolometric correction are then applied to obtain an estimate of the luminosity of the secondary. However, one can do better than this when, as for these 18 stars, the mass of the secondary is known. From the value of $\mu_{\min}$, $\mathfrak{M}_1$ is then obtained. The radii of the two stars are then obtained from Parenago's values of μ, R_1, and R_2, by noting that the products μR_1 and μR_2 are constants directly derivable from the observations. Assigning to the primary an effective temperature corresponding to its spectral type (Kuiper's Tables 3 and 13 were used [1938], as the spectral types are listed in the older notation), the bolometric magnitude of the primary can be obtained. By subtracting the bolometric correction (Kuiper's Table 6) we then obtain a consistent value for the absolute magnitude of the primary and could proceed, as before, to obtain the luminosity of the secondary. The theoretical curve on which this procedure depends is, however, at present somewhat crude.

The absolute magnitudes of the primaries were calculated by the foregoing method. Their masses were also obtained. The results are given in Table 1. Here M_1 and M_2 are the absolute magnitudes of the components; $\Delta\mathfrak{M}_1$ and ΔM_1 are the increments over the values listed by Parenago (main-sequence averages). It was found that, except in one instance, the increase of mass of the primary over the main-sequence average had the same algebraic sign as the increase in luminosity (neglecting any change in the bolometric correction with absolute magnitude for a given spectral type). On the other hand, 13 of the 18 primaries have a mass lower than the main-sequence average, and, of these, 12 lie below the main sequence in luminosity. Because of the small number of stars and some uncertainty as to the position of the theoretical curve, it is not possible to infer that the primaries tend to be systematically underluminous and undermassive. It is essential to note that the masses $\mathfrak{M}_1$ are extremely sensitive to an error in the theoretical curve's position, whereas the values of M_1 are not. The values of $\mathfrak{M}_1$ in Table 1 may therefore be quite wrong in some cases. The data appear to indicate that there is no marked tendency for the primaries to lie above the average main sequence. This is an indication that these systems are comparatively young or average members of population I.

III. EVOLUTIONARY MECHANISM

Let us consider in a general way the evolution of a close binary system subsequent to its formation at a given date by some unknown mechanism. One of the stars will, in

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general, be more massive than the other. The more massive star will, from the mass-luminosity relation, be much more luminous and will evolve more rapidly. At a certain point it will acquire an unstable depleted core (Schönberg and Chandrasekhar 1942) and begin to move very rapidly to the right in the H-R diagram (Sandage and Schwarzschild 1952), expanding its radius as it does so. It is then very probable that this expansion will continue until the star fills the inner zero-velocity surface. The star will then continue to expand but will not be able to hold on to the mass that passes out of the surface. This mass will either be collected by the companion or be ejected from the system by centrifugal force, probably depending on whether or not fairly violent ejection mechanisms, such as prominences, dominate. The material lost, lying at the surface of the star, will be rich in hydrogen; and, as mass is lost, the ratio of the mass contained in the depleted core to the total mass of the star will increase. This ratio is a measure of the "biological age" of the star. As this age increases, the expansion will continue. By this mechanism the star can gradually become less massive than its companion and eventually less luminous,

TABLE 1

Star	Sp1	Sp2	$\mathfrak{M}_2$	R_2	$\mathfrak{M}_1$	M_1	$\Delta\mathfrak{M}_1$	ΔM_1	M_2
RZ Cas.	A2	.....	0.34	1.82	0.92	+2.1	−2.1	+1.1	+4.3
RS Cep.	A5	G	.78	12.62	4.10	+0.8	+2.1	−1.3	+2.1
RW CrB.	A8	.....	.62	1.29	3.02	+1.8	+1.2	−0.9	+5.6
WW Cyg.	B8	G	.77	4.22	1.43	+1.2	−2.6	+1.7	+4.8
W Del.	A0	G5	.29	3.76	1.24	+1.2	−1.8	+1.0	+3.8
Z Dra.	A5	.....	.38	1.75	1.52	+2.1	−0.5	+0.1	+4.7
TW Dra.	A6	K2	.68	3.69	1.51	+1.3	−0.5	−0.9	+3.5
RW Gem	B6	F0	.58	3.95	1.49	+0.3	−3.5	+1.5	+2.0
TT Her.	A2	.....	.97	1.98	3.44	+0.1	+0.9	−1.0	+5.1
AK Her.	F8	.....	.32	0.72	0.82	+4.0	−0.4	+1.7	+4.2
Y Leo.	A3	.....	.52	2.15	1.34	+2.0	−0.9	+0.6	+5.2
T LMi	A0	.....	.13	1.91	0.49	+1.6	−2.5	+0.1	+4.7
Z Ori	B4	.....	.59	4.78	1.20	−1.2	−5.8	+0.7	+1.6
RT Per.	dF2	.....	.21	1.01	0.70	+3.7	−0.9	+0.4	+5.5
RW Per.	A5	gG0	.78	8.03	7.02	+0.7	+5.0	−1.3	+2.7
ST Per.	A3	G–K	.23	1.85	1.12	+2.0	−1.1	+0.5	+4.1
Y Psc.	A3	K0	.69	3.88	3.36	+1.1	+1.4	−0.4	+5.1
RZ Sct.	B2	.....	0.27	7.68	0.69	−1.6	−9.3	+1.3	+0.6

becoming the secondary component. It should be noted that if the star lies wholly inside the zero-velocity surface without losing mass, the dimensions of this surface will not alter. There is therefore no possibility of the surface itself expanding faster than the star. The dimensions of the surface will, of course, change as the mass ratio continuously decreases. The exact manner of this change will depend on the extent to which angular momentum is conserved in the system, i.e., the extent to which mass is exchanged or lost from the system. The main features of the 18 stars—low mass and subgiant character—seem to be qualitatively explained on the basis of the foregoing evolutionary mechanism. Conversely, one should not expect to find stars of this type among the single subgiants or the subgiant components of visual binary systems.

The fact that the peculiar stars are found only among the secondaries can perhaps be accounted for by remarking that the greater the fraction of mass a star has lost in this way, the more peculiar it will become and the greater chance it will have of being so classified. In addition, the amount of time spent in the lower-mass region is probably greater, so that there is more of a chance of observing a peculiar subgiant when it has lost considerable mass and probably become the secondary component of its system. An important question which is difficult to decide is whether or not mass is exchanged between

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the components. If so, the primary star would constantly have been receiving hydrogen-rich material from the outside and thus be kept "rejuvenated." The existence of such a process might enable one to attribute a greater age to such a system than is indicated by the early spectral type and moderate luminosity of the primary star.

In conclusion, we wish to cite an important paper by F. B. Wood (1950), in which a more detailed discussion of the mass-ejection mechanism in eclipsing binary systems is to be found. In this work Wood discusses the period fluctuations of eclipsing binaries and finds that they are associated with the same phenomenon (filling of the inner zero-velocity surface by the secondary component) as described here.

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