Astronomical and Astrophysical Transactions, 1998, Vol. 15, pp. 179–184
Reprints available directly from the publisher
Photocopying permitted by license only

SUBGIANT LUMINOSITY EXCESSES IN ECLIPSING BINARY SYSTEMS

V. G. KARETNIKOV

Departament of Astronomy, Odessa State University, T. G. Shevchenko Park, Odessa 270014, Ukraine

(Received June 3, 1996)

It has been shown that radius and temperature excesses are largest for subgiant stars in DS systems and low-mass and long-period SD systems, and smallest for subgiant stars in AR systems and low-mass and short-period SD systems. Subgiant stars in AR and more massive SD systems exhibit temperature deficiencies which are largest for the primaries of the AR systems. It is necessary to divide the class of SD systems into groups according to mass and orbital period while studying their properties.

KEY WORDS Stars: binary, statistics

Investigations of subgiant stars from eclipsing binary systems have shown that they possess luminosity excesses for their masses. The excesses are determined as the difference between the observed subgiant luminosities and those of mainsequence stars with similar masses. Generally, an excess indicates that the subgiant does not follow the mass–luminosity relation. At the same time subgiants in some cases show luminosity excesses, and in other cases have radii excesses, which are inherent to detached subgiants of DS systems (Batten, 1976).

Subgiant stars are present in three types of eclipsing binary stars. According to Svechnikov (1986) they can be companions in semi-detached systems (SD systems), in systems with a detached subgiant (DS systems) as well as primary and secondary stars in the eclipsing systems of AR Lacertae type (AR systems). In SD systems the subgiant completely fills up its Roche lobe, whereas in DS and AR systems the subgiant lies deep inside it. This testifies to the differences in subgiant star structure.

Let us consider the problem of the origin of luminosity excesses calculating them for subgiant stars of different types of eclipsing binary systems and dividing them into the following components: *a*, radius excesses; *b*, temperature excesses. To calculate the excesses we used data on stars' properties from Karetnikov and Andronov (1989); and from Karetnikov (1991) the averaged formulae of mass–radius and mass–temperature relations. We have also determined the correlations of excesses with binary system size A, subgiant mass M and stellar mass ratio q.

After the selection of programme stars the catalogue by Karetnikov and Andronov (1989), we obtained 82 SD stellar systems with companion masses M and orbital periods P ranging from 0.18 to $27M_{\odot}$ and 0.55 to 15.19 d, 11 DS systems with these magnitudes varying from 0.31 to $2.00M_{\odot}$ and 5.20 to 39.28 d and 12 stars of AR systems with the parameters 0.6–$2.31M_{\odot}$ and 1.98–7.33 d respectively. It is obvious that objects of the AR and DS system groups are not numerous, while there are many of SD systems and their parameters vary considerably.

We divide SD systems as follows: SD-a is a group that consists of the systems with low masses of components $M_i < 1.5$; SD-b, $10 > M_1 > 1.5 > M_2$; SD-c, $10 > M_1, M_2 > 1.5$; and SD-b, $M_1 > 10$, whereas $M_2 > 1.5M_{\odot}$. Here, the more massive star of the pair is denoted with index $i = 1$. The SD-b group is very numerous and consists of 58 objects. It can be divided into subgroups accordingly to period P: SD-1b for $P < 1.75$ d; SD-2b, $1.75 < P < 2.86$; SD-3b, $2.86 < P < 4.0$; and SD-4b, $P > 4.0$ d. Such designations and the numbers of stars n in the groups are given in tables below, where $\log A$ is the average distance between stars, $\log R$ is the average radius, $\log M$ is the average mass of the subgiants, q is the average ratio of stellar masses, $\Delta \log R$ is the average excess of radii, and $\Delta \log T$ is the average temperature excess of the subgiant.

Coefficients of correlation k(RA), k(RM), k(Rq) define the reliability of inter-connection of radii excesses $\Delta \log R$ for subgiants with distances between stars ($\log A$), subgiant masses ($\log M$) and mass ratio (q), while k(TA), k(TM), k(Tq) imply a reliability of inter-connection between temperature excess $\Delta \log T$ for subgiants with the same system characteristics. Relations between radii and temperature excesses and parameters of systems were calculated in the form of linear equations. The errors of calculation are given.

Table 1 demonstrates that all the systems containing subgiants show radii excesses. These exsesses are minimal for subgiants from AR systems (0.26) and maximal for subgiant stars from DS systems (0.73). These types of subgiants do not fill up their Roche lobes. The radii excesses of subgiants in SD systems, which fill up their Roche lobes, give average magnitudes (0.48). It should be noted that magnitude deviations from the average $\Delta \log R$ are similar for all types of system, but the number of SD stars in the sample is greater.

It follows from consideration of the data for SD systems divided into groups according to their masses (SD-a, -b, -c, -d) that within the scatter, the magnitudes of $\Delta \log R$ have a tendency to increase with increase in system size ($\log A$). It is clearly seen after dividing of group SD-b on the basis of orbital period value (SD-1b, -2b, -3b, -4b), where an obvious increase of radii excess with orbital period occurs. One can assume that this is the result of the Roche lobe size increase and subsequently subgiant size on filling up their lobes. Correlation between $\Delta \log R$ and $\log A$ is rather high among SD systems, an exception being group of SD-d.

A comparison of radii excesses with masses of stars (Table 1) shows that maximal and minimal $\Delta \log R$ are observed in detached subgiants of lower (DS systems) and higher masses (AR systems). Although in subgiants of the SD-b group having low masses, but with orbital periods of more than 4 days, the average radii excesses (0.78) slightly exceed the average magnitude for DS systems (0.73). However, for

Table 1. **Average parameters of subgiants of eclipsing binary systems, dispersion of the averaging, and magnitudes of excesses of radii and temperature $\Delta \log R$ and $\Delta \log T$ (RiA is the filling up of the Roche lobe)**

Type of system	*n*	*log A* ε	*log R* ε	*RiA* ε	*log M* ε	*q* ε	Δ*log R* ε	Δ*log T* ε
SD	82	1.12	0.54	1.00	–0.06	0.31	0.48	0.06
		0.26	0.26	0.10	0.42	0.15	0.22	0.15
DS	11	1.51	0.74	0.67	–0.15	0.29	0.73	0.05
		0.14	0.16	0.16	0.19	0.09	0.19	0.13
AR1	12	1.19	0.47	0.53	0.15	0.89	0.27	-0.10
		0.10	0.21	0.19	0.09	0.16	0.20	0.08
AR2	12	1.19	0.43	0.51	0.08	0.89	0.26	–0.06
		0.10	0.18	0.20	0.13	0.16	0.21	0.07
SD-a	6	0.74	0.15	1.03	–0.46	0.26	0.33	0.17
		0.14	0.12	0.06	0.18	0.11	0.16	0.11
SD-b	58	1.08	0.50	1.01	–0.20	0.28	0.52	0.08
		0.20	0.18	0.09	0.25	0.12	0.22	0.14
SD-c	12	1.23	0.60	1.00	0.31	0.36	0.38	–0.03
		0.12	0.10	0.07	0.09	0.10	0.09	0.14
SD-d	6	1.69	1.13	0.93	0.95	0.55	0.41	–0.05
		0.18	0.26	0.21	0.34	0.28	0.27	0.16
SD-1b	15	0.84	0.29	0.98	–0.13	0.38	0.26	0.04
		0.08	0.10	0.10	0.16	0.11	0.10	0.11
SD-2b	14	1.03	0.45	1.00	–0.19	0.29	0.46	0.07
		0.06	0.08	0.06	0.24	0.12	0.11	0.12
SD-3b	14	1.15	0.55	1.04	–0.21	0.23	0.58	0.09
		0.08	0.11	0.05	0.26	0.08	0.07	0.15
SD-4b	15	1.32	0.70	1.03	–0.29	0.22	0.78	0.12
		0.10	0.09	0.12	0.28	0.09	0.16	0.15

low-mass and short-period systems of the SD-1b group, as well as in the SD-a group, observed radii excesses are the same as in AR systems (0.26). Thus, radii excesses in subgiants of the SD systems show a great variety, while stars of the SD-b group illustrate a growth of radii excess with orbital period increase and with stellar mass ratio q decrease.

In analysing temperature excesses calculated for subgiant stars of various system types, a temperature deficiency is found in stars of AR systems. A lower temperature deficiency is also observed in subgiant stars of SD systems (SD-c, -d groups) with masses over $1.5 M_{\odot}$. For subgiant stars of the same classes having masses lower than $1.5 M_{\odot}$, temperature excesses on average are regularly seen and they have higher values than in subgiant stars of DS systems. So, the conclusion that temperature excesses $\Delta \log T$ are inherent only to low-massive subgiants, seems to be reliable. It is confirmed by the high significance of the relation between $\Delta \log T$ excesses and subgiant masses in SD and DS systems.

Let us consider the variation in temperature excess in subgiants of SD systems and their subdivision into groups. Average magnitudes of excesses are small and are often less than the dispersion of the averaging. Nevertheless, it can be seen that

Table 2. Relation coefficients of radii excesses $\Delta \log R$ with magnitudes $\log A$, $\log M$ and q in employing a formula of the type $y = a + bx$ for the case of significance for correlation coefficient k (blank space in the table denotes the absence of a significant correlation)

Type of system	n	a_1 σ	b_1 σ	$k(RA)$ σ	a_2 σ	b_2 σ	$k(RM)$ σ	a_3 σ	b_3 σ	$k(Rq)$ σ
SD	82	0.00	0.42	0.51	0.46	−0.22	−0.42	0.07	−0.73	−0.70
		0.09	0.08	0.10	0.02	0.05	0.10	0.05	0.08	0.08
DS	11		–			–			–	
AR1	12		–			–			–	
AR2	12		–			–			–	
SD-a	6	−0.46	1.08	0.93		–			–	
		0.15	0.20	0.18						
SD-b	58	−0.50	0.94	0.83	0.41	0.54	−0.68	0.02	0.84	−0.78
		0.09	0.08	0.08	0.03	0.09	0.11	0.06	0.09	0.08
SD-c	12	−0.46	0.68	0.88		–			–	
		0.15	0.12	0.15						
SD-d	6		–			–			–	
SD-1b	15		–		0.22	−0.33	−0.56		–	
					0.03	0.14	0.23			
SD-2b	14		–		0.38	−0.39	−0.88	0.18	−0.48	−0.79
					0.02	0.06	0.14	0.05	0.09	0.18
SD-3b	14	1.20	−0.54	−0.60	0.53	−0.23	−0.89	0.35	−0.34	−0.74
		0.24	0.20	0.23	0.01	0.03	0.13	0.06	0.08	0.20
SD-4b	15		–		0.63	−0.51	−0.88	0.28	−0.70	−0.85
					0.03	0.08	0.13	0.06	0.08	0.14

there is a tendency of temperature excess growth with decrease of subgiant mass and increase of orbital period. Correlation coefficients are highly significant for the relation of excess $\Delta \log T$ with subgiant mass, with stellar mass ratio and quite insignificant as compared with system size $\log A$. Based upon our calculations, temperature excesses of subgiants are apparently caused by mass loss.

Earlier (Karetnikov, 1987) it was shown that SD systems can be divided into two groups, one of which consists of the SD systems with mass ratio of the pair q less than 0.25 and subgiants with greatest luminosity excesses. This conclusion is confirmed by examining Table 1. Objects of the SD-3b group, SD-4b and most of the stars of the SD-a group can be attributed to this group. However, for subgiant stars of the SD-a group there is no dependence upon orbital period as is observed for the SD-3b and SD-4b groups. This factor seems to be a secondary one and unconnected with this characteristic.

Let us analyse the data of Table 2 listing the formula coefficients of the form $y = a + bx$ for the relation of $\log R$ with $\log A$, $\log M$ and q. As seen, coefficients a and b can be found only for SD systems where correlations are of sufficient significance (level $= 0.02$). Insignificance of such relations for subgiants of DS and AR systems can be due to the paucity of sampling. For semi-detached stars in the SD-a group, the strongest dependence of radii excess upon size of binary system ($b = 1.08$) was obtained. This dependence becomes weaker with subgiant mass growth. For the

Table 3. Relation coefficients of temperature excess $\Delta \log T$ with magnitudes $\log A$, $\log M$ and q in employing a formula of the type $y = c + dx$ taking into account the significance of correlation coefficient k (blank space shows correlations to be insignificant)

Type of system	n	c_1	d_1	$k(TA)$	c_2	d_2	$k(TM)$	c_3	d_3	$k(Tq)$
		σ	σ	σ	σ	σ	σ	σ	σ	σ
SD	82				0.04	–0.25	–0.70	–0.25	–0.56	–0.80
					0.01	0.03	0.08	0.03	0.05	0.07
DS	11		–		–0.03	–0.54	–0.80		–	
					0.03	0.14	0.20			
AR1	12		–			–			–	
AR2	12		–		–0.03	–0.33	–0.56		–	
					0.02	0.16	0.26			
SD-a	6				–0.11	–0.62	–0.99	–0.20	–0.61	–0.95
					0.02	0.04	0.07	0.06	0.09	0.16
SD-b	58				–0.01	–0.47	–0.86	–0.25	–0.56	–0.74
					0.01	0.04	0.07	0.03	0.05	0.09
SD-c	12		–			–			–	
SD-d	6		–			–			–	
SD-1b	15		–		–0.03	–0.54	–0.81	–0.25	–0.67	–0.80
					0.02	0.11	0.16	0.05	0.12	0.16
SD-2b	14		–		–0.01	–0.42	–0.89	–0.23	–0.52	–0.76
					0.02	0.06	0.13	0.06	0.10	0.19
SD-3b	14		–		–0.01	–0.48	–0.86	–0.42	–0.77	–0.75
					0.03	0.08	0.15	0.11	0.16	0.19
SD-4b	15		–		–0.01	–0.46	–0.84	–0.34	–0.66	–0.87
					0.03	0.08	0.15	0.06	0.08	0.14

SD-d group, such a relation becomes insignificant. Radii excesses are significantly related to subgiant mass and stellar mass ratio of the SD-b group and are not dependent on period P.

Relations of temperature excesses $\Delta \log T$ for subgiants with magnitudes $\log A$, $\log M$ and q (using a formula of the type $y = c + dx$) are given in Table 3. As is seen from the table, there are no significant correlations between temperature excess and size of binary system. However, formulae for temperature excess and subgiant mass relations are reliable for low-mass stars. The value of $\Delta \log T$ rapidly increases when the subgiant mass of the SD-a group decreases. This effect is less pronounced in AR systems. For subgiants with masses of nearly $1.5 M_\odot$, correlations of $\Delta \log T$ with $\log M$ and q are insignificant.

We can state that the earlier inference about the presence of large radii excesses in detached subgiants is true only for DS systems. For detached subgiants of AR stars radii excesses are smallest. The large number of SD systems permit us to study the problem more comprehensive and confirm that radii excesses increase when subgiant masses are lowered and binary sizes increase. This is clearly seen from the comparison of $\Delta \log R$ of the SD system during their subdivision into groups on the basis of mass. SD stars yield both large (SD-4b) and small (SD-1b) $\Delta \log R$.

For subgiants of SD systems, reliable relations between radii excess and size of binary system are obtained, which are numerically different for groups of stars with different masses. SD systems with large masses are an exception. The following results can be considered as reliable: (1) the formulae of the relation of radii excess and subgiant mass of the SD-b group and (2) their isolation based on the orbital period values. In the latter case, it should be noted that the shorter period SD-1b pairs give less reliable relations than more long-period low-mass binary systems. The same correlational pattern is seen as a result of radii excess comparison with mass ratio q for the same types of star.

On average, in detached subgiant stars of AR systems instead of expected excesses, a temperature deficiency is found. It is greater in the more massive star of the pair. The same is observed in SD systems with subgiant masses over $1.5M_{\odot}$. In detached subgiants of DS systems, the temperature excesses are small, while in semi-detached subgiants these are present only in low-mass systems. By subdividing SD-b stars into groups on the basis of P, we can see that $\Delta \log T$ increases with log A increase. This is, however, probably caused by the decrease of subgiant mass.

Comparison of average groups values of $\Delta \log R$ and $\Delta \log T$ shows them to make a different contribution to the total luminosity excess. The contribution of radii excess to luminosity excess exceeds that of temperature excess approximately 100 times. Therefore, temperature deficiency sometimes observed in a subgiant has no strong influence on the total luminosity excess. At the same time, as noted above, temperature excesses for the class of SD systems correlate better with luminosity excesses than do radii excesses.

References

Batten, A. (1976) *Binary and Multiple Stars*, Mir, Moscow.

Karetnikov, V. G. (1987) *Astron. Tsirk.*, No. 1492, 3.

Karetnikov, V. G. (1991) *Astron. Zh.* **68**, 880.

Karetnikov, V. G. and Andronov, I. L. (1989) *Statistic Properties of Eclipsing Binary Stars at the Stage of the First Mass Exchange*, Kiev, Manuscript of UkrNIINTI, No. 2629–89.

Svechnikov, M. A. (1986) *Catalogue of Orbital Elements, Masses and Luminosities of Close Binary Stars*, Irkutsk.