STELLAR MASSES AND RADII BASED ON MODERN BINARY DATA

Petr Harmanec

Astronomical Institute, Czechoslovak Academy of Sciences, 251 65 Ondřejov, Czechoslovakia

Received 19 January 1988

ЗВЕЗДНЫЕ МАССЫ И РАДИУСЫ ОПРЕДЕЛЕННЫЕ ПО СОВРЕМЕННЫМ ДАННЫМ О ДВОЙНЫХ СИСТЕМАХ

Собраны и проанализированы точные данные по размерам и массам затменных двойных, найденные в астрономической литературе после 1980 года. Выведены простые аппроксимационные формулы связывающие эффективную температуру и другие основные величины (массу, радиус, болометрическую звездную величину). Средние и экстремальные значения для каждого спектрального класса даются тоже в виде таблицы. Сделано сравнение с другими данными, собранными раньше. Коротко обсуждается влияние улучшенных данных на определение критических периодов и скоростей вращения для звезд ранних спектральных классов.

Accurate data on absolute dimensions of eclipsing binaries published in the astronomical literature since 1980 are collected and analyzed. Simple approximation formulae relating the effective temperature with other basic physical parameters (mass, radius, bolometric magnitude) are derived. Mean and extreme values of these parameters for each spectral type are also tabulated. Comparison with some previous data sets on stellar masses and radii is carried out and the implication of improved data for the problem of critical rotational periods and equatorial velocities of early-type stars is briefly discussed.

Key words: stellar masses and radii — eclipsing binaries — critical rotational velocities and periods — LQ And

1. Introduction

Our present knowledge of accurate stellar masses, radii and other basic physical parameters rests almost exclusively on the data derived from the orbital and light-curve solutions for some "well-behaving" detached binaries. Popper (1980) published an excellent critical compilation of available accurate data on absolute dimensions of binaries. His study has been the best and the most reliable source of information about stellar masses and radii. However – since Popper has not published either approximation formulae or a table of mean values for each spectral class – some investigators preferred to use other sources. For instance, students of B-type stars have often used the tabular data on masses and radii published by Underhill (1982).

At about the same time when Popper published his review, the new revolution in stellar astronomy (caused by the introduction of signal-generating detectors into stellar spectroscopy and by a massive use of computers) began. Several groups of investigators started systematic spectroscopic and photometric observations of eclipsing binaries. To date, they have published quite a significant number of new data on absolute dimensions of component stars based on accurate observations and sophisticated data analyses. In most cases, these new data are superior to the data, which were available to Popper before 1980.

The first evaluation of new observational data for OB stars has recently been published by Hilditch and Bell (1987). Their study mainly deals with the mass-luminosity relation and some evolutionary considerations.

It is often useful to know normal stellar masses, radii and luminosities as a function of spectral type. Accurate knowledge of these data can be critical for the evaluation of critical rotational velocities and periods of stars, for instance. This is, why I decided to collect and analyze accurate data on stellar masses and radii and derive some simple approximation formulae between various parameters. I am publishing this compilation for the convenience of other interested colleagues and to demonstrate that the improvement of our knowledge of masses and radii of stars may have a serious impact on the understanding of some phenomena.

Bull. Astron. Inst. Czechosl. 39 (1988), 329—345.

2. New Data On Absolute Dimensions

Table 1 is a collection of new accurate data on stellar masses, radii, bolometric magnitudes, spectral types and projected rotational velocities, which I was able to find in the astronomical literature published since 1980. My compilation is in all probability incomplete, but it should be fairly representative as I tried to include the main series of papers published by the most active investigators in the field, which were available to me by the end of 1987.

As reliable data on the O and early B stars are still rather rare, I have also included some data on these stars, which are definitely less accurate than the typical data of Table 1. Generally speaking, the most accurate are the data on detached systems included in Part A of the Table. The accuracy is correspondingly lower for semi-detached and contact (or nearly contact) systems included into Parts B and C of the Table, respectively. The data are arranged in order of increasing right ascension in each part of the Table.

The Sun is added at the end of the Table, adopting the values $T_{\rm eff} = 5780$ K ($\log T_{\rm eff} = 4{\cdot}762$) and $M_{\rm bol} = 4{\cdot}69^{\rm m}$ following Popper (1980). For the same reason of consistency I have recalculated all bolometric magnitudes and surface gravities in Part A of Table 1 from the effective temperatures, radii and masses accepted by the original authors using the formulae

$$(1) \quad M_{\rm bol} = 42{\cdot}31 - 5 \log R/R_\odot - 10 \log T_{\rm eff}\,,$$

and

$$(2) \quad \log g = 4{\cdot}438 + \log M/M_\odot - 2 \log R/R_\odot \quad [\mathrm{CGS}]\,,$$

which are based on the above-quoted values for the Sun. For non-spherical stars of Parts B and C of Tab. 1, these quantities were only re-calculated (using formulae (1) and (2)) if they were not given by the original authors.

3. Mean Data and Approximation Formulae

To derive masses, radii and bolometric magnitudes of normal main-sequence stars for each spectral subclass, I considered the data of Part A of Tab. 1 and also the data of Popper's (1980) Tabs 2, 4, 7, and 8, omitting, of course, those binaries, for which more recent data are available in Part A of Tab. 1 here. For convenience, the data adopted from Popper are reproduced in condensed form in Tab. 2. $M_{\rm bol}$ and $\log g$ (not given by Popper) were again calculated using formulae (1) and (2). The data in Tab. 2 are arranged in the sequential order of Popper's Tabs 2, 4, 7, and 8. Altogether, 169 data points were considered.

The second step of the analysis was that I conservatively omitted all stars with $\log g$ smaller than 3·9 [CGS] to exclude probable subgiants from the sample. (This criterion may appear a bit too crude for OB stars and too weak for late-type stars, but I found

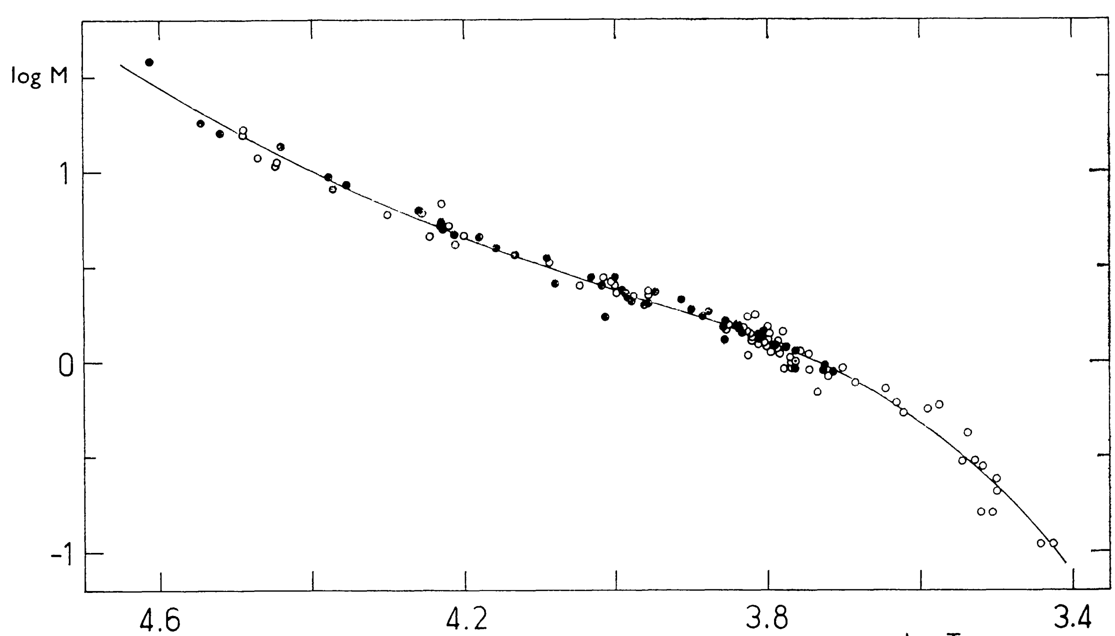

Fig. 1. Logarithm of stellar mass (in solar units) as a function of effective temperature. New data from Tab. 1 (Part A) are shown as black circles, those from Popper (1980) as white circles (see the text for details). The mean relation (3) is shown as a solid line.

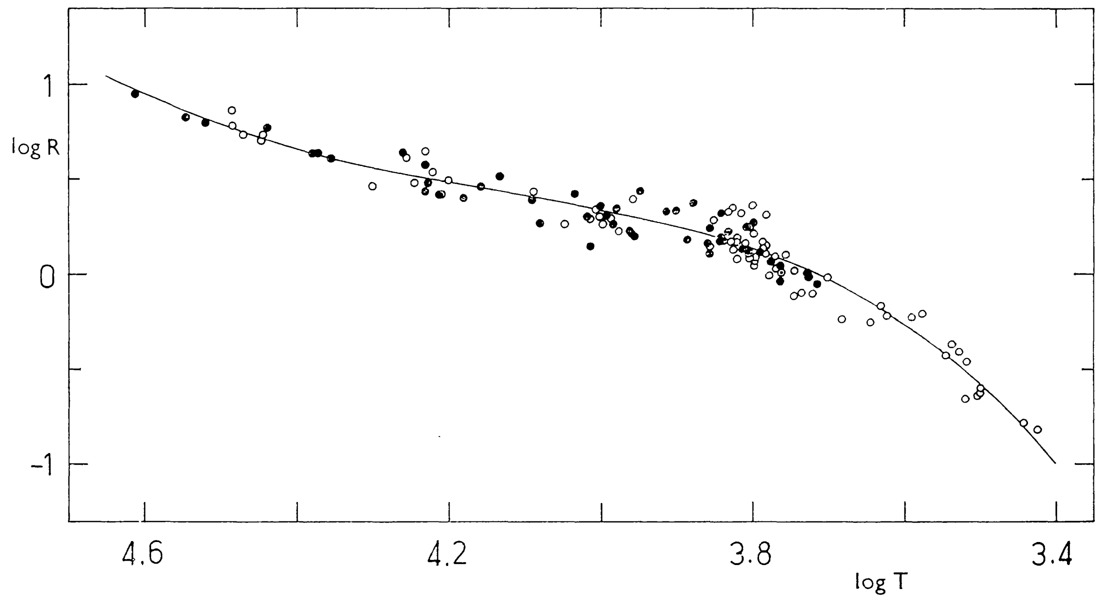

Fig. 2. Logarithm of stellar radius (in solar units) as a function of effective temperature. Notations as in Fig. 1.

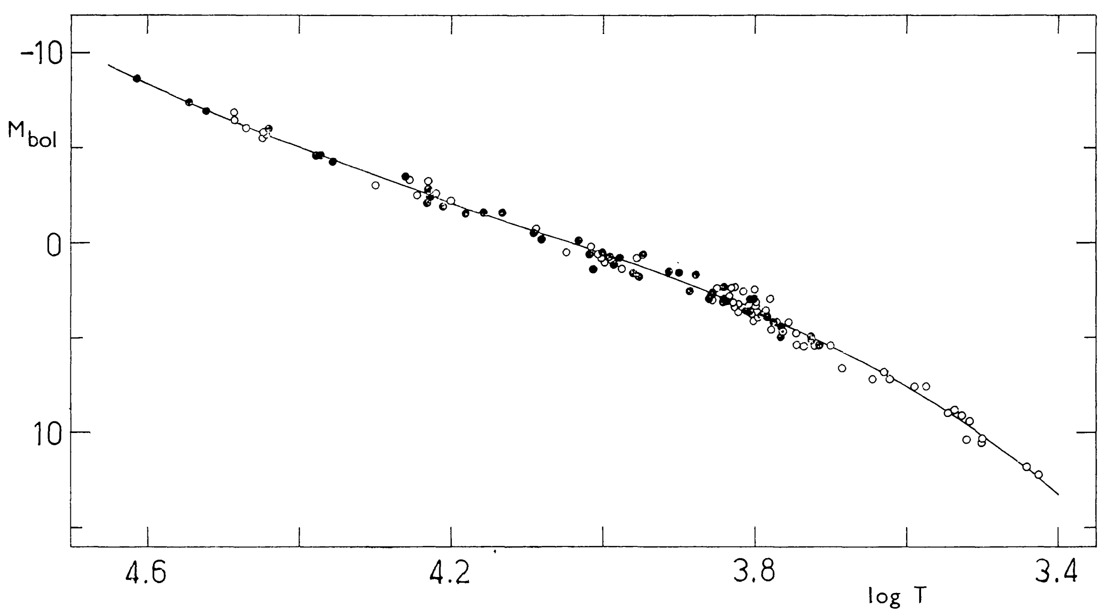

Fig. 3. Bolometric magnitude as a function of effective temperature. Notations as in Fig. 1.

it quite practical in application to the data available in Tabs. 1 and 2.) Another precaution was to omit all known Am stars and consider them separately. All the remaining 140 stars were used in constructing Figs 1 to 3, where the mass and radius (in logarithmic representation) and bolometric magnitude are shown as functions of the effective temperature. The data of Tab. 1 (Part A) and Tab. 2 are shown using different symbols. It is seen that all three functions are well defined by the available data, the scatter being reasonably small in all cases. At the same time, all three functions are significantly non-linear even in the logarithmic representation used, having inflections at both high-temperature and low-temperature ends.

The following polynomial approximation (obtained by the least-squares fit to the data via Chebyshev polynomials) were found to provide a good fit to the data over the whole range of effective temperatures:

(3)

$$\log M/\mathrm{M}_\odot = (((-1{\cdot}744951X + 30{\cdot}31681)X - 196{\cdot}2387)X + 562{\cdot}6774)X - 604{\cdot}0760\,,$$

$$\log R/\mathrm{R}_\odot = (((-0{\cdot}8656627X + 16{\cdot}22018)X - 112{\cdot}2303)X + 341{\cdot}6602)X - 387{\cdot}0969\,,$$

and

$$M_{\mathrm{bol}} = (((4{\cdot}328314X - 81{\cdot}10091)X + 561{\cdot}1516)X - 1718{\cdot}301)X + 1977{\cdot}795\,,$$

Table 1

Accurate absolute dimensions of eclipsing binaries from the recent astronomical literature

Binary	Sp. class	log T_{eff}	$M/M_\odot$	log $M/M_\odot$	$R/R_\odot$	log $R/R_\odot$	log g	M_{bol}	$v \sin i$	$v_S \sin i$	$v_{PS} \sin i$	O−S	O−PS	P/e	Ref.
A. Detached systems															
ζ Phe	B 6 V	4·158	0·93 (5)	0·594	2·85 (2)	0·455	4·122	−1·54	85 (8)	86	—	−0·1	—	1·670	1
HD 6 882	B 8 V	4·079	2·55 (3)	0·407	1·85 (2)	0·267	4·309	0·18	75 (8)	56	—	2·3	—	0	
AI Phe	F 7 V	3·800	1·195 (4)	0·078	1·816 (24)	0·259	3·997	3·01	4 (1)	4	5	0·3	−1·0	24·592	2
HD 6 980	K 0 IV	3·700	1·236 (5)	0·092	2·930 (48)	0·467	3·596	2·98	6 (1)	6	8	0·0	−2·1	0·189	
IQ Per	B 7·5	4·090	3·51 (4)	0·545	2·45 (3)	0·389	4·205	−0·54	68 (2)	71	83	−1·5	−7·5	1·744	3
HD 24 909	A 6	3·885	1·73 (2)	0·238	1·50 (2)	0·176	4·324	2·58	44 (2)	44	51	0·0	−3·5	0·075	
EW Ori	G 0 V	3·776	1·190 (14)	0·076	1·142 (10)	0·058	4·40	4·26	—					6·937	4
HD 287 727	G 5 V	3·762	1·154 (14)	0·062	1·091 (10)	0·038	4·42	4·50	—					0·068	
TZ Men	B 9·5 V	4·017	2·487 (25)	0·396	2·016 (20)	0·304	4·225	0·62	16 (4)	12	13	1·0	0·7	8·569	5
HD 39 780	A 9	3·857	1·504 (10)	0·177	1·432 (15)	0·156	4·303	2·96	12:	8	9			0·035	
HS Aur	G 8 V	3·728	0·898 (19)	−0·047	1·005 (23)	0·002	4·39	5·02	—					9·815	4
	K0V	3·716	0·877 (17)	−0·057	0·874 (30)	−0·058	4·50	5·44	—					0	
GZ CMa	(A 2 m)	3·945	2·20 (3)	0·342	2·49 (3)	0·396	3·99	0·88	—					4·801	6
HD 56 429	(A 3 m)	3·931	2·00 (3)	0·301	2·13 (4)	0·328	4·08	1·36	—					0	
PV Pup	A 8 V	3·840	1·565 (12)	0·195	1·542 (16)	0·188	4·256	2·97	43 (4)	47	52	−1·0	−2·2	1·661	7
HD 62 863	A 8 V	3·841	1·554 (14)	0·191	1·499 (16)	0·176	4·278	3·02	43 (4)	45	50	−0·5	−1·7	0·0503	
VV Pyx	A 1 V	3·978	2·098 (18)	0·322	2·167 (20)	0·336	4·088	0·85	23 (3)	24	29	−0·3	−2·0	4·596	8
HD 71 581	A 1 V	3·978	2·098 (18)	0·322	2·167 (20)	0·336	4·088	0·85	23 (3)	24	29	−0·3	−2·0	0·0956	
RS Cha	A 5 V	3·900	1·86 (2)	0·270	2·14 (6)	0·330	4·05	1·66	71 (7)	64	—	1·0	—	1·670	9
HD 75 747	A 7 V	3·877	1·82 (2)	0·260	2·34 (6)	0·369	3·96	1·69	71 (7)	70	—	0·1	—	0	
KW Hya	A 3 m	3·903	1·978 (36)	0·296	2·126 (15)	0·328	4·079	1·64	15 (2)	14	17	0·5	−1·0	7·750	10
HD 79 193	(F 0)	3·838	1·488 (17)	0·173	1·484 (22)	0·171	4·268	3·07	13 (2)	10	12	1·5	0·5	0·0945	
QX Car	B 2 V	4·377	9·27 (12)	0·967	4·29 (6)	0·632	4·140	−4·62	120	48	89	4·5	1·0	4·478	11
HD 86 118	B 2 V	4·354	8·48 (12)	0·928	4·05 (6)	0·607	4·151	−4·27	110	46	84	5·8	2·3	0·278	
DM Vir	F 6·5 V	3·806	1·457 (25)	0·163	1·764 (19)	0·246	4·108	3·02	—					4·669	12
HD 123 423	F 6·5 V	3·806	1·457 (25)	0·163	1·764 (19)	0·246	4·108	3·02	—					0	
5 α CrB	B 9·5 IV	3·987	2·58 (5)	0·412	3·04 (30)	0·483	3·89	0·03	110	9	21	9·1	8·0	17·360	13
HD 139 006	G 5 V	3·763	0·92 (3)	−0·036	0·90 (4)	−0·046	4·50	4·91	—					0·370	
V 760 Sco	B 4 V	4·228	4·98 (9)	0·697	3·01 (6)	0·479	4·18	−2·36	95 (10)	87	92	0·8	0·3	1·731	14
HD 147 683	B 4 V	4·212	4·62 (7)	0·665	2·64 (5)	0·422	4·26	−1·92	85 (10)	76	81	0·9	0·4	0·0265	

V 539 Ara	B 3 V	4·26	6·25 (7)	0·796	4·43 (12)	0·646	3·94	−3·52	75 (8)	71	79	0·5	−0·5	3·169	1
HD 161 783	B 4 V	4·23	5·33 (6)	0·727	3·73 (25)	0·572	4·02	−2·85	48 (5)	60	66	−2·4	−3·6	0·056	
V 1647 Sgr	A 1 V	3·982	2·19 (4)	0·340	1·83 (2)	0·262	4·253	1·18	80 (5)	28	75	10·4	1·0	3·283	15
HD 163 708	A 2 V	3·959	1·97 (3)	0·294	1·67 (2)	0·223	4·289	1·61	70 (5)	26	68	8·8	0·4	0·413	
V 451 Oph	B 9 V	4·033	2·78 (6)	0·444	2·64 (3)	0·422	4·038	−0·13	41 (7)	61	62	−2·8	−3·0	2·197	16
HD 170 470	A 0 V	3·991	2·36 (5)	0·373	2·03 (3)	0·307	4·196	0·86	30 (5)	47	48	−3·4	−3·6	0·0125	
DI Her	B 4 V	4·23	5·15 (10)	0·712	2·68 (5)	0·428	4·29	−2·13	34	12	43	5·5	−2·2	10·550	17
HD 175 227	B 5 V	4·18	4·52 (6)	0·655	2·48 (5)	0·394	4·30	−1·46	51	12	40	7·8	2·2	0·489	
V 1182 Aql	O 6 V	4·613	37·8 (1·6)	1·577	8·8 (2)	0·944	4·12	−8·54	220 (30)	241	—	−0·7	—	1·622	18
HD 175 514	B 1	4·439	13·5 (5)	1·130	5·9 (1)	0·771	4·03	−5·93	150 (40)	162	—	−0·3	—	0	
V 805 Aql	A 2	3·913	2·11 (4)	0·324	2·11 (12)	0·324	4·11	1·56	—					2·408	19
HD 177 708	(A 9)	3·856	1·63 (2)	0·212	1·75 (12)	0·243	4·16	2·54	—					0	
FL Lyr	F 8 V	3·789	1·218 (16)	0·086	1·283 (30)	0·108	4·31	3·88	30 (2)	30	—	0·0	—	2·178	4
HD 179 890	G 8 V	3·724	0·958 (11)	−0·019	0·963 (30)	−0·016	4·45	5·15	25 (2)	22	—	1·5	—	0	
V 1143 Cyg	F 5 V	3·810	1·391 (16)	0·143	1·346 (23)	0·129	4·323	3·57	18 (2)	9	35	4·5	−8·5	7·641	20
HD 185 912	(F 5·5)	3·806	1·347 (13)	0·129	1·323 (23)	0·122	4·324	3·64	28 (3)	9	35	6·3	−2·3	0·540	
V 380 Cyg	B 1·5 III	4·389	14·3 (6)	1·155	17·1	1·233	3·11	−7·75	100 (5)	69	110	6·2	−2·0	12·426	21
HD 187 879	B 2 V	4·373	8·0 (3)	0·903	4·3	0·633	4·06	−4·59	40 (10)	17	28	2·3	1·2	0·218	
V 442 Cyg	F 1	3·839	1·56 (2)	0·193	2·07 (3)	0·316	4·00	2·34	46 (3)	44	—	0·7	—	2·386	22
HD 334 426	F 2	3·833	1·41 (2)	0·149	1·66 (3)	0·220	4·15	2·88	33 (3)	35	—	−0·7	—	0	
EE Peg	A 3 Vm	3·913	2·01 (6)	0·303	2·02 (6)	0·305	4·13	1·65	—					2·628	19
HD 206 155	F 6	3·856	1·29 (3)	0·111	1·27 (6)	0·104	4·34	3·23	—					0	
EK Cep	A 1·5 V	3·954	2·02 (1)	0·305	1·58 (2)	0·199	4·35	1·78	23 (2)	18	23	2·5	0·0	4·428	23
HD 206 821	G 5	3·755	1·12 (1)	0·049	1·32 (2)	0·121	4·25	4·16	10·5 (2)	15	19	−2·2	−4·2	0·109	
WX Cep	(A 5 m)	3·911	2·535 (50)	0·404	4·00 (3)	0·602	3·64	0·19	—					3·378	24
HD 213 631	(A 2)	3·948	2·325 (45)	0·366	2·71 (3)	0·433	3·94	0·66	—					0	
AH Cep	O 8 V	4·544	18·1 (9)	1·258	6·7 (2)	0·826	4·04	−7·26	175 (15)	179	—	−0·2	—	1·775	25
HD 216 014	O 9 V	4·521	15·9 (8)	1·201	6·2 (2)	0·792	4·06	−6·86	180 (20)	165	—	0·7	—	0	
PV Cas	B 9·5	4·000	2·79 (5)	0·446	2·27 (5)	0·356	4·17	0·53	65	65	70	0·0	−0·7	1·750	24
HD 240 208	B 9·5	4·000	2·79 (5)	0·446	2·27 (5)	0·356	4·17	0·53	65	65	70	0·0	−0·7	0·0322	
AL Scl	B 6 V	4·132	3·63 (11)	0·560	3·24 (5)	0·511	3·98	−1·56	90	66	77	2·6	1·4	2·445	26
HD 224 113	B 9 V	4·013	1·17 (4)	0·233	1·40 (2)	0·146	4·38	1·45	103	29	33	7·1	6·7	0·074	

B. Semi-detached systems

DM Per	B 5 V	4·201	5·82 (24)	0·765	3·96 (10)	0·598	4·01	−2·65	—					2·728	27
HD 14 871	A 5 III	3·915	1·83 (7)	0·262	4·59	0·662	3·38	−0·10	—					0	

(Table 1 (Cont.)

Binary	Sp. class	log T_{eff}	$M/M_\odot$	log $M/M_\odot$	$R/R_\odot$	log $R/R_\odot$	log g	M_{bol}	$v \sin i$	$v_S \sin i$	$v_{PS} \sin i$	O—S	O—PS	P/e	Ref.
TT Aur	B 2 Vn	4·373	8·58 (10)	0·933	4·06 (3)	0·609	4·16	—4·46	—					1·333	28
HD 33 088	B 4	4·267	5·56 (10)	0·745	4·17 (3)	0·620	3·94	—3·46	—					0	
TT Aur	B 1	4·395	8·7	0·940	3·9	0·591	4·19	—4·60	—						29
HD 33 088	B 2·5	4·254	5·6	0·748	4·3	0·633	3·93	—3·40	—						
RY Gem	A0Ve	3·973	2·36	0·373	2·5	0·398	4·0	0·6	—					9·301	30
HD 58 713	K 0 IV	3·635	0·38	—0·420	5·8	0·763	2·5	2·2	—					0·16	
AI Cru	B 2 IVe	4·384	10·3 (2)	1·013	4·95 (6)	0·695	4·06	—5·00	170 (10)	177	—	—0·7	—	1·418	31
	(B 4)	4·248	6·3 (1)	0·799	4·43 (6)	0·646	3·95	—3·40	150 (10)	158	—	—0·8		0	
19 δ Lib	A 0 V	3·974	4·9 (2)	0·690	4·1	0·613	3·90	—0·49	—					2·327	32
HD 132 742	G:		1·7 (2)	0·230	4·2	0·623	3·42							0·069	
u Her	B 2 III—V	4·301	7·6 (6)	0·881	5·8 (3)	0·763	3·79	—4·51	—					2·051	33
HD 156 633	B 8·5	4·064	2·9 (2)	0·462	4·4 (3)	0·643	3·61	—1·54	—					0	
RY Aqr	A 7	3·881	1·27 (6)	0·104	1·28 (4)	0·107	4·44	2·6	—					1·967	33
HD 203 069	(G 8 III)	3·658	0·26 (1)	—0·585	1·79 (6)	0·253	3·34	4·5	—					0	
						C. Contact and nearly contact systems									
AO Cas	O 8·5 III	4·540	24·6 (2·9)	1·391	13·2 (9)	1·121	3·59	—8·69	—					3·523	35
HD 1 337	O 8·5 III	5·544	29·2 (4·7)	1·465	14·4 (1·0)	1·158	3·59	—8·92	—					0	
SX Aur	B 1·5	4·398	10·3 (4)	1·013	5·17 (9)	0·713	4·02	—5·24	201 (5)	216	—	—3·1	—	1·210	28
HD 33 357	B 3	4·275	5·6 (3)	0·748	3·90 (7)	0·591	4·00	—3·40	92 (29)	163	—	—2·5	—	0	
LY Aur	O 9·5 III	4·506	28 (3)	1·447	15·6 (6)	1·193	3·50	—8·72	—					4·025	36
HD 35 921	(B 0·5)	4·461	16 (3)	1·204	12·0 (8)	1·079	3·48	—7·70	—					0	
LY Aur	09·5 III	4·514	31·6 (3·2)	1·500	16·4 (2·0)	1·215	3·51	—8·90	—						37
HD 35 921	B 0 III	4·486	21·0 (4·7)	1·322	13·4 (1·6)	1·127	3·51	—8·19	—						
V Pup	B 1 V	4·450	14·86 (24)	1·172	6·18 (7)	0·791	4·03	—6·10	220 (10)	215	—	0·5	—	1·455	38
HD 65 818	B 2—3	4·425	7·76 (14)	0·890	4·90 (5)	0·690	3·95	—5·34	200 (10)	171	—	2·9		0	
RZ Pyx	(B 4)	4·230	5·27 (16)	0·722	2·61 (5)	0·417	4·33	—2·08	200 (20)	201	—	—0·1		0·656	39
HD 75 920	(B 4)	4·224	4·33 (13)	0·636	2·44 (3)	0·387	4·30	—1·88	190 (20)	188	—	0·1		0	
V 348 Car	(B 0 III)	4·473	32 (4)	1·505	18·8 (1·4)	1·274	3·40	—8·7	—					5·562	40
HD 90 707	B 1 III	4·418	29 (4)	1·462	19·3 (1·4)	1·286	3·33	—8·2	—					0	
TU Mus	O 7·5	4·526	23·5	1·371	8·0	0·903	4·0	—7·4	285 (25)	292	—	—0·3		1·387	41
HD 100 213	(B 0)	4·471	15·8	1·199	6·6	0·820	4·0	—6·4	240 (25)	241	—	—0·0		0	

V 701 Sco	B 2: nn	4·371	10·3	1·013	4·30	0·633	4·18	—4·6	—	0·762	42
HD 317 844	(B 2)	4·367	10·3	1·013	4·28	0·631	4·18	—4·5	—	0	
V 701 Sco	B 1	4·37	9·1 (5)	0·959	3·93 (7)	0·594	4·21	—4·3	—		43
HD 317 844	B 1	4·37	9·1 (5)	0·959	3·93 (7)	0·594	4·21	—4·3	—		
DH Cep	O 5·5 V	4·628	52 (12)	1·716						2·111	44
HD 215 835	O 6·5 V	4·597	42 (12)	1·623						0	

D. The Sun

	G2 V	4·762	1·000	0·000	1·000	0·000	4·438	4·69			

Notes: The errors of masses and radii, expressed as the uncertainty in the last digit quoted, and accepted from the original papers, are given in brackets following the respective quantities. The values of $v \sin i$ for DI Her are my estimates from the published line profiles. The spectral types estimated from the published $\log T_{eff}$ are given in brackets. The column "P/e" contains the orbital periods and eccentricities, symbols S and PS refer to synchronous and pseudosynchronous rotation, respectively (see the text for a more detailed discussion). The data are from the following papers (see column "Ref."): 1 — Andersen1983, 2 — Andersen et al. 1988, 3 — Lacy and Frueh 1985, 4 — Popper et al. 1986, 5 — Andersen et al. 1987b, 6 — Popper et al. 1985, 7 — Vaz and Andersen 1984, 8 — Andersen et al. 1984a, 9 — Clausen and Nordström 1980, 10 — Andersen and Vaz 1984, 11 — Andersen et al. 1983a, 12 — Andersen et al. 1984b, 13 — Tomkin and Popper 1986, 14 — Andersen et al. 1985, 15 — Andersen and Giménez 1985, 16 — Clausen et al. 1986, 17 — Popper 1982a, 18 — Bell et al. 1987b, 19 — Popper 1981, 20 — Andersen et al. 1987a, 21 — Hill and Batten 1984, 22 — Lacy and Frueh 1987, 23 — Popper 1987a, 24 — Popper 1987b, 25 — Bell et al. 1986, 26 — Haefner et al. 1987, 27 — Hilditch et al. 1986, 28 — Bell et al. 1987a, 29 — Wachmann et al. 1986, 30 — Plavec and Dobias 1987, 31 — Bell et al. 1987c, 32 — Tomkin 1978, 33 — Hilditch 1984, 34 — Helt 1987, 35 — Schneider and Leung 1978, 36 — Li and Leung 1985, 37 — Popper 1982b, 38 — Andersen et al. 1983b, 39 — Bell and Malcolm 1987b, 40 — Hilditch and Lloyd Evans 1985, 41 — Andersen and Gronbech 1975, 42 — Bell and Malcolm 1987a, 43 — Andersen et al. 1980, 44 — Lines et al. 1986

Table 2

Basic parameters of stars from Popper's (1980) compilation, which were considered here. The stars with log g smaller than 3·9 were not used to the construction of the mean relations (3).

Sp. type	log T_{eff}	$M/M_\odot$	log $M/M_\odot$	$R/R_\odot$	log $R/R_\odot$	log g	M_{bol}	Binary
B 9	4·063	3·61	0·558	4·39	0·642	3·711	−1·53	Chi 2 Hya
A 0	4·005	2·64	0·422	2·16	0·334	4·191	0·59	
B 8	4·088	3·31	0·520	2·70	0·431	4·095	−0·73	AS Cam
B 9	4·001	2·51	0·400	2·00	0·301	4·236	0·80	
B 9	4·015	2·75	0·439	2·44	0·387	4·103	0·22	RX Her
A 0	3·985	2·33	0·367	1·96	0·292	4·221	1·00	
B 8	4·048	2·48	0·394	1·83	0·262	4·308	0·52	AR Aur
B 9	3·997	2·29	0·360	1·83	0·262	4·273	1·03	
A 1	3·955	2·35	0·371	2·49	0·396	4·017	0·78	Beta Aur
A 1	3·955	2·27	0·356	2·49	0·396	4·002	0·78	
A 7	3·885	2·28	0·358	3·62	0·559	3·679	0·67	SZ Cen
A 7	3·878	2·32	0·365	4·55	0·658	3·487	0·24	
A 7 m	3·890	2·10	0·322	3·00	0·477	3·806	1·02	V 624 Her
A 7 m	3·882	1·80	0·255	2·20	0·342	4·008	1·78	
A 8 m	3·880	2·00	0·301	2·50	0·398	3·943	1·52	RR Lyn
F 0	3·850	1·55	0·190	1·93	0·286	4·057	2·38	
A 5 m	3·910	1·98	0·297	1·89	0·276	4·182	1·83	WW Aur
A 7 m	3·890	1·82	0·260	1·89	0·276	4·145	2·03	
A 2 m	3·935	1·88	0·274	1·59	0·201	4·309	1·95	CM Lac
F 0	3·855	1·47	0·167	1·42	0·152	4·301	3·00	
F 0 m	3·848	1·81	0·258	2·20	0·342	4·011	2·12	MY Cyg
F 0 m	3·845	1·78	0·250	2·20	0·342	4·004	2·15	
A 2 m	3·940	1·78	0·250	1·52	0·182	4·325	2·00	V 477 Cyg
F 2	3·820	1·34	0·127	1·20	0·079	4·407	3·71	
F 0	3·840	1·68	0·225	2·54	0·405	3·854	1·89	EI Cep
F 2	3·827	1·78	0·250	2·80	0·447	3·794	1·80	
A 8 m	3·875	1·76	0·246	1·88	0·274	4·135	2·19	XY Cet
A 9 m	3·860	1·63	0·212	1·88	0·274	4·102	2·34	
F 2	3·824	1·72	0·236	2·22	0·346	3·981	2·34	ZZ Boo
F 2	3·824	1·72	0·236	2·22	0·346	3·981	2·34	
A 8 m	3·863	1·62	0·210	1·58	0·199	4·250	2·69	TX Her
F 2	3·827	1·45	0·161	1·48	0·170	4·259	3·19	
F 2	3·830	1·52	0·182	2·11	0·324	3·971	2·39	CW Eri
F 2	3·820	1·28	0·107	1·48	0·170	4·205	3·26	
F 5	3·800	1·51	0·179	2·26	0·354	3·909	2·54	RZ Cha
F 5	3·800	1·51	0·179	2·26	0·354	3·909	2·54	
F 8	3·785	1·27	0·104	1·48	0·170	4·201	3·61	BK Peg
F 8	3·780	1·43	0·155	2·03	0·307	3·978	2·97	
F 7	3·798	1·40	0·146	1·74	0·241	4·103	3·13	CD Tau
F 7	3·798	1·31	0·117	1·61	0·207	4·142	3·30	
F 2	3·820	1·39	0·143	1·50	0·176	4·229	3·23	TV Cet
F 5	3·803	1·27	0·104	1·26	0·100	4·341	3·78	
F 5	3·808	1·37	0·137	1·44	0·158	4·258	3·44	BS Dra
F 5	3·808	1·37	0·137	1·44	0·158	4·258	3·44	
F 5	3·810	1·34	0·127	1·36	0·134	4·298	3·54	HS Hya
F 5	3·803	1·28	0·107	1·22	0·086	4·372	3·85	
F 5	3·812	1·23	0·090	1·35	0·130	4·267	3·54	VZ Hya
F 6	3·798	1·12	0·049	1·12	0·049	4·389	4·08	
F 8	3·785	1·17	0·068	1·28	0·107	4·292	3·92	UX Men
F 8	3·782	1·11	0·045	1·28	0·107	4·269	3·95	
F 8	3·785	1·12	0·049	1·34	0·127	4·233	3·82	WZ Oph
F 8	3·785	1·12	0·049	1·34	0·127	4·233	3·82	
G 2	3·768	0·99	−0·004	1·08	0·033	4·367	4·46	UV Leo
G 2	3·768	0·92	−0·036	1·08	0·033	4·335	4·46	

Table 2 (Cont.)

Sp. type	log T_{eff}	$M/M_\odot$	log $M/M_\odot$	$R/R_\odot$	log $R/R_\odot$	log g	M_{bol}	Binary
M 1	3.576	0.59	−0.229	0.62	−0.208	4.624	7.59	YY Gem
M 1	3.576	0.59	−0.229	0.62	−0.208	4.624	7.59	
M 4	3.500	0.24	−0.620	0.25	−0.602	5.022	10.32	CM Dra
M 4	3.500	0.21	−0.678	0.235	−0.629	5.018	10.45	
O9.8	4.485	16.7	1.223	6.0	0.778	4.104	−6.43	Y Cyg
O9.8	4.485	16.7	1.223	6.0	0.778	4.104	−6.43	
O9.8	4.485	15.6	1.193	7.3	0.863	3.904	−6.86	V 478 Cyg
O9.8	4.485	15.6	1.193	7.3	0.863	3.904	−6.86	
B 0.4	4.470	14.5	1.161	8.6	0.934	3.730	−7.06	V 453 Cyg
B 0.7	4.445	11.3	1.053	5.4	0.732	4.026	−5.80	
B 0.4	4.470	11.8	1.072	5.4	0.732	4.045	−6.05	CW Cep
B 0.7	4.445	11.1	1.045	5.0	0.699	4.085	−5.64	
B 1.5	4.390	10.8	1.033	8.1	0.908	3.654	−6.13	Alpha Vir
B 4	4.230	6.8	0.833	4.4	0.643	3.984	−3.21	
B 3	4.255	6.10	0.785	4.05	0.607	4.008	−3.28	CV Vel
B 3	4.255	6.00	0.778	4.05	0.607	4.001	−3.28	
B 3	4.300	5.90	0.771	2.90	0.462	4.284	−3.00	BM Ori
B 5	4.220	5.16	0.713	3.43	0.535	4.080	−2.57	U Oph
B 5	4.200	4.60	0.663	3.11	0.493	4.115	−2.15	
B 4	4.245	4.53	0.656	3.00	0.477	4.140	−2.53	AG Per
B 5	4.210	4.12	0.615	2.60	0.415	4.223	−1.87	
G 8	3.745	1.11	0.045	1.02	0.010	4.463	4.81	ADS 10 598
G 8	3.745	1.11	0.045	1.02	0.010	4.463	4.81	
F 7	3.794	1.19	0.076	1.22	0.085	4.344	3.95	Delta Equ
F 7	3.794	1.19	0.076	1.22	0.085	4.344	3.95	
F 9	3.782	1.19	0.076	1.38	0.140	4.234	3.79	12 Per
F 9	3.770	1.04	0.017	1.23	0.090	4.275	4.16	
A 1	3.975	2.20	0.342	1.68	0.225	4.330	1.43	Alpha CMa
F 5	3.816	1.77	0.248	2.06	0.314	4.058	2.58	Alpha CMi
G 0	3.765	1.25	0.097	2.24	0.350	3.834	2.91	Zeta Her
K 0	3.735	0.70	−0.155	0.79	−0.100	4.483	5.46	
G 2	3.755	1.14	0.057	1.27	0.105	4.285	4.23	Alpha Cen
K 0	3.700	0.93	−0.032	0.94	−0.025	4.457	5.44	
F 0	3.826	1.08	0.033	1.35	0.130	4.211	3.40	Gamma Vir
F 0	3.826	1.08	0.033	1.35	0.130	4.211	3.40	
G 0	3.777	0.91	−0.041	0.98	−0.010	4.417	4.59	Eta Cas
M 0	3.590	0.56	−0.252	0.59	−0.230	4.646	7.56	
G 8	3.745	0.90	−0.046	0.77	−0.115	4.623	5.44	Ksi Boo
K 4	3.645	0.72	−0.143	0.55	−0.260	4.815	7.16	
K 0	3.721	0.84	−0.076	0.79	−0.100	4.563	5.60	70 Oph
K 5	3.631	0.61	−0.215	0.68	−0.170	4.453	6.85	
K 3	3.685	0.78	−0.108	0.58	−0.240	4.811	6.66	HR 6 426
K 5	3.622	0.54	−0.268	0.60	−0.220	4.610	7.19	
M 4.5	3.538	0.42	−0.377	0.43	−0.370	4.800	8.78	Wolf 630
M 4.5	3.538	0.42	−0.377	0.43	−0.370	4.800	8.78	
M 3	3.546	0.30	−0.523	0.37	−0.430	4.775	9.00	Fu 46
M 3.5	3.528	0.30	−0.523	0.39	−0.410	4.735	9.08	
M 3	3.518	0.28	−0.553	0.35	−0.460	4.804	9.43	Kr 60
M 4.5	3.503	0.16	−0.796	0.23	−0.640	4.922	10.48	
M 4.5	3.520	0.16	−0.796	0.22	−0.660	4.961	10.41	o^2 Eri BC
M 5.5	3.443	0.11	−0.959	0.16	−0.790	5.060	11.83	L 726−8
M 5.5	3.425	0.11	−0.959	0.15	−0.820	5.12	12.16	

Table 3

Mean and extreme observed masses, radii and bolometric magnitudes of normal main-sequence stars as functions of spectral type

Spectral class	log T_{eff}	Mass					Radius					Bolometric magnitude					No. of stars
		Observed			Calculated		Observed			Calculated		Observed			Calculated		
		Min	Max	Mean	All data	New only	Min	Max	Mean	All data	New only	Min	Max	Mean	All data	New only	
O 6	4·620			37·8	*31·65*	34·88			8·8	*9·85*	9·78			−8·54	*−8·86*	−8·84	1
O 7	4·585				*26·07*	27·42				*8·54*	8·30				*−8·20*	−8·14	0
O 8	4·551			18·1	*21·66*	22·05			6·7	*7·51*	7·18			−7·26	*−7·58*	−7·48	1
O 9	4·521			15·9	*18·47*	18·41			6·2	*6·75*	6·40			−6·86	*−7·04*	−6·93	1
O 9·5	4·497				*16·30*	16·06				*6·23*	5·88				*−6·63*	−6·51	0
B 0	4·475	15·6	16·7	16·1 (6)	*14·57*	14·25	6·0	7·3	6·65 (65)	*5·80*	5·47	−6·43	−6·86	−6·65 (22)	*−6·26*	−6·13	4
B 0·5	4·455	11·1	14·5	12·2 (8)	*13·19*	12·84	5·0	8·6	6·10 (84)	*5·46*	5·14	−5·63	−7·06	−6·14 (32)	*−5·92*	−5·80	4
B 1	4·418			13·5	*11·03*	10·70			5·9	*4·91*	4·63			−5·93	*−5·33*	−5·20	1
B 2	4·364	8·0	9·27	8·58 (37)	*8·62*	8·39	4·05	4·3	4·21 (8)	*4·28*	4·06	−4·27	−4·62	−4·49 (11)	*−4·48*	−4·37	3
B 3	4·280	5·90	6·25	6·06 (7)	*6·07*	6·00	2·90	4·43	3·86 (33)	*3·56*	3·43	−3·00	−3·52	−3·27 (11)	*−3·24*	−3·16	4
B 4	4·235	4·53	6·8	5·24 (34)	*5·12*	5·11	2·64	4·4	3·24 (28)	*3·26*	3·17	−1·92	−3·21	−2·50 (19)	*−2·61*	−2·55	6
B 5	4·190	4·12	5·16	4·60 (21)	*4·36*	4·39	2·48	3·43	2·91 (22)	*3·01*	2·95	−1·46	−2·57	−2·01 (23)	*−1·98*	−1·94	4
B 6	4·149	3·63	3·93	3·78 (15)	*3·80*	3·85	2·85	3·24	3·05 (20)	*2·81*	2·77	−1·54	−1·56	−1·55 (1)	*−1·42*	−1·39	2
B 7	4·112			3·51	*3·38*	3·43			2·45	*2·65*	2·62			−0·54	*−0·92*	−0·90	1
B 8	4·063	2·48	3·31	2·78 (27)	*2·91*	2·96	1·83	2·70	2·13 (29)	*2·44*	2·43	0·52	−0·73	−0·01 (37)	*−0·26*	−0·25	3
B 9	4·015	1·71	2·78	2·41 (20)	*2·52*	2·56	1·40	2·64	2·06 (22)	*2·25*	2·24	1·45	−0·13	0·67 (28)	*0·40*	0·41	5
B 9·5	3·995	2·49	2·79	2·69 (10)	*2·38*	2·41	2·02	2·27	2·19 (8)	*2·17*	2·16	0·62	0·53	0·56 (3)	*0·68*	0·68	3
A 0	3·974	2·33	2·64	2·44 (10)	*2·24*	2·26	1·96	2·16	2·05 (6)	*2·09*	2·08	1·00	0·59	0·82 (12)	*0·97*	0·98	3
A 1	3·959	2·02	2·35	2·18 (4)	*2·14*	2·16	1·58	2·49	2·06 (14)	*2·03*	2·02	1·78	0·78	1·09 (15)	*1·18*	1·19	7
A 2	3·943	1·97	2·33	2·11 (8)	*2·04*	2·05	1·58	2·71	2·02 (26)	*1·97*	1·95	1·78	0·66	1·40 (25)	*1·41*	1·43	4
A 3	3·932				*1·98*	1·98				*1·92*	1·91				*1·57*	1·59	0
A 4	3·922				*1·92*	1·92				*1·88*	1·87				*1·72*	1·73	0
A 5	3·911			1·86	*1·86*	1·86			2·14	*1·84*	1·82			1·66	*1·88*	1·90	1
A 6	3·900			1·73	*1·79*	1·79			1·50	*1·79*	1·77			2·58	*2·04*	2·06	1
A 7	3·890			1·82	*1·74*	1·73			2·34	*1·75*	1·73			1·69	*2·19*	2·22	1
A 8	3·875	1·55	1·57	1·56 (1)	*1·66*	1·65	1·50	1·54	1·52 (2)	*1·69*	1·67	3·02	2·97	3·00 (2)	*2·42*	2·45	2
A 9	3·859	1·50	1·63	1·57 (6)	*1·58*	1·56	1·43	1·75	1·59 (16)	*1·62*	1·60	2·96	2·54	2·75 (21)	*2·67*	2·70	2
F 0	3·844	1·08	1·55	1·33 (10)	*1·50*	1·48	1·35	1·93	1·51 (11)	*1·56*	1·53	3·40	2·38	3·05 (19)	*2·90*	2·94	5
F 1	3·835			1·56	*1·46*	1·44			2·07	*1·52*	1·50			2·34	*3·05*	3·09	1
F 2	3·826	1·28	1·72	1·48 (6)	*1·41*	1·39	1·20	2·22	1·73 (14)	*1·48*	1·46	3·71	2·34	2·92 (18)	*3·19*	3·23	8
F 3	3·821				*1·39*	1·37				*1·46*	1·43				*3·28*	3·32	0
F 4	3·815				*1·36*	1·34				*1·44*	1·41				*3·37*	3·42	0
F 5	3·810	1·23	1·77	1·37 (5)	*1·33*	1·31	1·22	2·06	1·42 (8)	*1·42*	1·39	3·85	2·58	3·49 (12)	*3·46*	3·50	9
F 6	3·802	1·12	1·46	1·33 (8)	*1·30*	1·28	1·12	1·76	1·48 (17)	*1·38*	1·35	4·08	3·02	3·34 (25)	*3·59*	3·64	4

F 7	3·793	1·19	1·40	1·26 (4)	*1·25*	1·23	1·22	1·82	1·52 (13)	*1·34*	1·31	3·94	3·01	3·46 (20)	*3·74*	3·79	5
F 8	3·785	1·11	1·43	1·21 (4)	*1·22*	1·20	1·28	2·03	1·43 (10)	*1·31*	1·28	3·95	2·97	3·71 (13)	*3·88*	3·93	7
F 9	3·779	1·04	1·19	1·12 (8)	*1·19*	1·17	1·23	1·38	1·31 (8)	*1·28*	1·25	4·16	3·79	3·98 (19)	*3·98*	4·03	2
G 0	3·772	0·91	1·19	1·05 (14)	*1·16*	1·14	0·98	1·14	1·06 (8)	*1·25*	1·22	4·26	4·59	4·43 (17)	*4·10*	4·16	2
G 1	3·770				*1·15*	1·13				*1·24*	1·21				*4·14*	4·19	0
G 2	3·768	0·92	1·14	1·01 (5)	*1·14*	1·12	1·00	1·27	1·11 (6)	*1·23*	1·20	4·69	4·23	4·46 (9)	*4·17*	4·23	4
G 3	3·766				*1·13*	1·11				*1·23*	1·19				*4·21*	4·26	0
G 4	3·764				*1·12*	1·10				*1·22*	1·19				*4·25*	4·30	0
G 5	3·762	0·92	1·15	1·04 (12)	*1·11*	1·10	0·90	1·09	1·00 (10)	*1·21*	1·18	4·91	4·50	4·71 (21)	*4·28*	4·33	2
G 6	3·754				*1·08*	1·06				*1·17*	1·14				*4·42*	4·48	0
G 7	3·746				*1·04*	1·03				*1·14*	1·11				*4·57*	4·62	0
G 8	3·738	0·90	1·11	1·00 (5)	*1·01*	0·99	0·77	1·02	0·96 (5)	*1·10*	1·08	5·44	4·81	5·05 (12)	*4·72*	4·77	5
G 9	3·727				*0·96*	0·95				*1·06*	1·03				*4·92*	4·98	0
K 0	3·715	0·70	0·93	0·84 (5)	*0·91*	0·90	0·79	0·94	0·85 (4)	*1·01*	0·98	5·60	5·43	5·48 (4)	*5·15*	5·21	4
K 1	3·703				*0·86*	0·86				*0·96*	0·93				*5·38*	5·44	0
K 2	3·690				*0·81*	0·81				*0·90*	0·88				*5·64*	5·69	0
K 3	3·671			0·78	*0·73*	0·74			0·58	*0·82*	0·80			6·66	*6·02*	6·08	1
K 4	3·652			0·72	*0·66*	0·68			0·55	*0·75*	0·73			7·16	*6·42*	6·47	1
K 5	3·633	0·54	0·61	0·58 (4)	*0·59*	0·62	0·60	0·68	0·64 (4)	*0·68*	0·66	7·19	6·85	7·02 (17)	*6·83*	6·88	2
K 6	3·619				*0·55*	0·57				*0·62*	0·61				*7·14*	7·18	0
K 7	3·604				*0·50*	0·53				*0·57*	0·56				*7·49*	7·52	0
K 8	3·599				*0·48*	0·52				*0·55*	0·55				*7·61*	7·63	0
K 9	3·594				*0·47*	0·50				*0·54*	0·53				*7·72*	7·75	0
M 0	3·589			0·56	*0·45*	0·49			0·59	*0·52*	0·51			7·56	*7·84*	7·86	1
M 1	3·571	0·59	0·59	0·59 (0)	*0·40*	0·44	0·62	0·62	0·62 (0)	*0·46*	0·46	7·59	7·59	7·59 (0)	*8·28*	8·29	2
M 2	3·556				*0·36*	0·40				*0·42*	0·42				*8·66*	8·65	0
M 3	3·542	0·28	0·30	0·29 (1)	*0·32*	0·37	0·35	0·37	0·36 (1)	*0·38*	0·38	9·43	9·00	9·22 (22)	*9·02*	8·99	2
M 3·5	3·535			0·30	*0·30*	0·36			0·39	*0·36*	0·36			9·08	*9·20*	9·17	1
M 4	3·528	0·21	0·24	0·22 (2)	*0·29*	0·34	0·23	0·25	0·24 (1)	*0·34*	0·34	10·46	10·32	10·39 (7)	*9·39*	9·35	2
M 4·5	3·520	0·16	0·42	0·29 (8)	*0·27*	0·32	0·22	0·43	0·33 (6)	*0·32*	0·32	10·48	8·78	9·61 (48)	*9·61*	9·55	4
M 5	3·513				*0·25*	0·31				*0·30*	0·31				*9·80*	9·73	0
M 5·5	3·505	0·11	0·11	0·11 (0)	*0·24*	0·30	0·15	0·16	0·15 (1)	*0·28*	0·29	12·16	11·83	12·00 (17)	*10·02*	9·94	2
M 6	3·497				*0·22*	0·28				*0·26*	0·27				*10·25*	10·16	0
M 7	3·459				*0·15*	0·22				*0·19*	0·20				*11·38*	11·20	0
M 8	3·418				*0·10*	0·16				*0·12*	0·14				*12·69*	12·41	0

Note that the calculated values for new data, based on formulae (4), are extrapolated for spectral types later than K 0. All masses and radii are in solar units.

where

$$X = \log T_{\rm eff} .$$

These formulae are defined for $4{\cdot}62 \geqq \log T_{\rm eff} \geqq$ $\geqq 3{\cdot}425$. They are shown as solid lines in Figs 1 to 3.

The following approximation formulae were derived using only new data in Part A of Tab. 1 (54 stars):

(4)

$$\log M/\mathrm{M}_\odot = ((1{\cdot}771141X - 21{\cdot}46965)\,X + 88{\cdot}05700)\,X - 121{\cdot}6782\,,$$
$$\log R/\mathrm{R}_\odot = ((2{\cdot}166639X - 26{\cdot}91528)\,X + 112{\cdot}1089)\,X - 156{\cdot}1170\,,$$
$$M_{\rm bol} = ((-10{\cdot}83320X + 134{\cdot}5764)\,X - 570{\cdot}5446)\,X + 822{\cdot}8952\,,$$

where again

$$X = \log T_{\rm eff} .$$

They are only defined in the more limited range of

$$4{\cdot}62 \geqq \log T_{\rm eff} \geqq 3{\cdot}71 .$$

The accuracy of the data used certainly varies from star to star and one could consider assigning different weights to the individual data points. I am afraid, however, that the formal errors of the data, given by the original authors, do not properly reflect the inherent accuracy in every case. Generally speaking, it is not easy to find an objective way of assigning weights to the data based on combined spectroscopic and photometric observations. Given the reasonably small scatter in Figs 1 to 3, I therefore preferred a conservative approach to the analysis and used unweighted data to determine the approximation formulae (3).

To characterize the present uncertainties in the determination of the basic physical parameters considered here, and to provide a practical table of mean values for future use, I constructed Table 3, which contains mean as well as extreme *observed* values of mass, radius, and bolometric magnitude for each spectral subclass, and also mean values calculated using formulae (3) and (4) and Popper's (1980) scale of effective temperatures (which is still satisfactory and accepted by most investigators in the field). In my opinion, the mean values calculated via formulae (3), which represent smoothed averages defined by the whole body of available data, give the best available estimates of the mean masses, radii and bolometric magnitudes of normal main-sequence stars, and should be used in future applications. It is clear, however, that rather large uncertainties still remain for stars of spectral types earlier than B 2 and later than K0. Only obtaining absolute dimensions for more detached binaries in these spectral ranges can improve the situation. Note, in particular, the rather critical discrepancy between Popper's (1980) scale of effective temperatures and the spectral classification of L 726−8 (see his Tab. 8), the system which defines the cool end of the sequence. Both components are classified M 5·5 V, but their quoted effective temperatures would correspond to M 7 and M 8, respectively.

It is, however, encouraging to note the very good mutual agreement of the values calculated from all, and only new data, notably even outside the range of applicability of formulae (4). This in a sense justifies the conservative approach to the analysis used and increases the credibility of the mean values derived here.

4. Comparison With Some Other Compilations

Two sources of data on masses and radii of stars have been widely used besides Popper's (1980) compilation, namely Straižys and Kuriliene (1981) and Underhill (1982). The mean masses and radii from both compilations are compared with the mean relations (3) derived here in Fig. 4a, b, using the scales of effective temperatures defined by the respective authors. The comparison of the data by Straižys and Kuriliene illustrates well the uncertainties at both ends of the spectral sequence. Otherwise, the mutual agreement is acceptable, the slight systematic differences observed lie within the scatter defined by the observational data (compare Figs 1 and 2 to Fig. 4). This is not true for the masses and radii of B stars compiled by Underhill. Her values for all mid-B stars lie systematically *above* the range of values defined by the observational data used here, and these differences cannot be accounted for by the slight differences between Underhill's and Popper's scale of effective temperatures. As it will be demonstrated below, the revision of the masses and radii will have some important consequences for understanding B stars, because Underhill's values were widely used in the recent astronomical literature dealing with B and Be stars.

5. Critical Rotational Periods And Break-Up Velocities of B Stars

The importance of the improved values of masses and radii of normal stars can be demonstrated on the particular example of critical rotational periods and

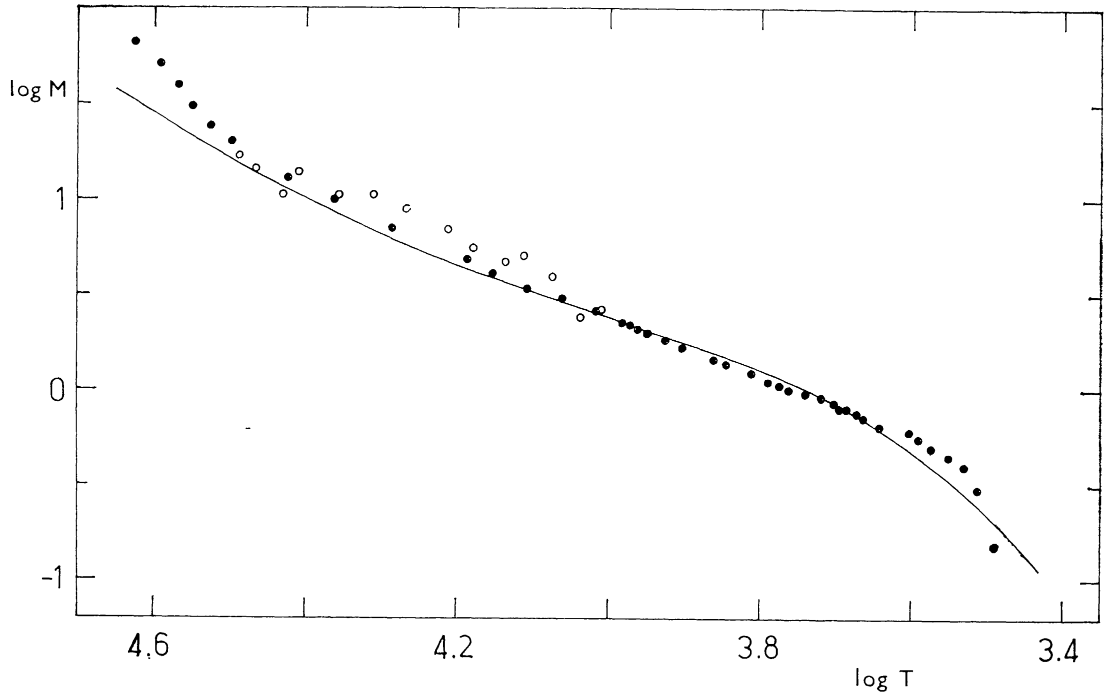

Fig. 4a

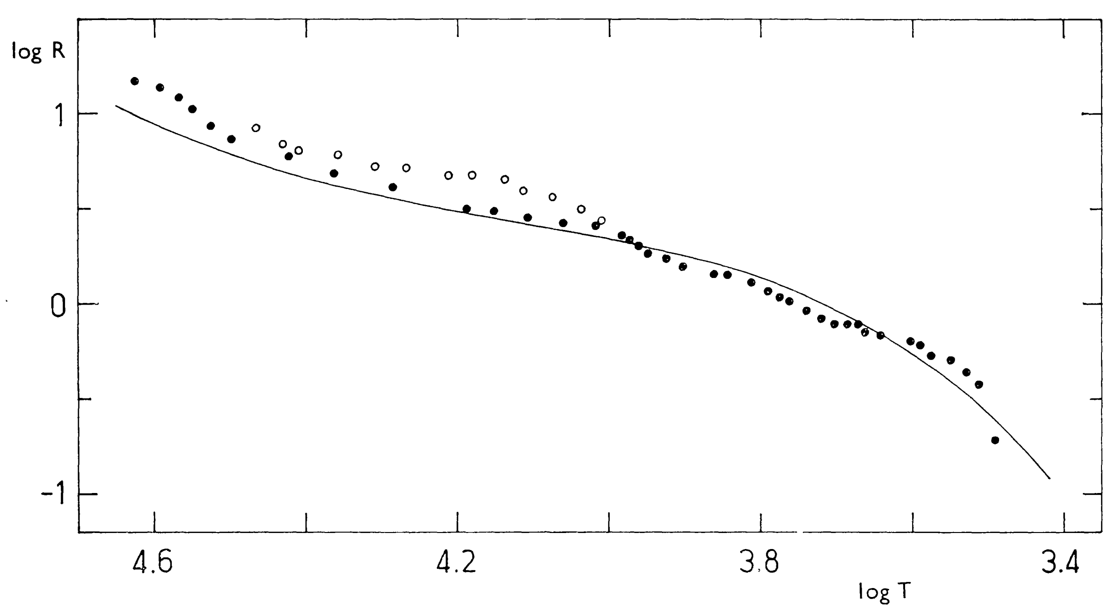

Fig. 4b

Fig. 4. Comparison of the mean relations (3) derived here with the mean masses (a) and radii (b) of normal main-sequence stars tabulated by Straižys and Kuriliene (1981) (black circles) and by Underhill (1982) (white circles).

break-up velocities of B stars. Table 4 compares Underhill's and the new data. The critical (minimum stable) rotational periods $P_{\rm crit}$ and equatorial break-up velocities $V_{\rm crit}$ were calculated using the well-known formulae

(5) $P_{\rm crit} = 0{\cdot}1159 R/\mathrm{R}_\odot ((R/\mathrm{R}_\odot)/(M/\mathrm{M}_\odot))^{1/2}$

and

(6) $V_{\rm crit} = 436{\cdot}\bar{6}((M/\mathrm{M}_\odot)/(R/\mathrm{R}_\odot))^{1/2}$.

There is, however, a certain problem with the application of formulae (5) and (6) to data obtained statistically. It is clear that stars rotating near break-up must be rotationally flattened so that their equatorial radius R_e should be entered for R in (5) and (6). As long as the Roche model for a single star can be considered as a good approximation of the star's surface, the relation between the polar (R_p) and equatorial radius is $R_e = 1{\cdot}5R_p$ for the stars rotating at break-up, but decreases rapidly to $R_e = R_p$ for decreasing rotation rates. The polar radius of a rotating star is nearly identical with the radius of a corresponding non-rotating star (c.f. Stoeckley and Buscombe 1987). On the other hand, it is usually either an equatorial or mean radius that is determined for eclipsing binaries.

To bracket the uncertainties discussed above, I have tabulated the critical velocities and periods in Tab. 4 for the two extreme assumptions i.e. taking $R_e = R$ and $R_e = 1{\cdot}5R$.

The differences between Underhill's and the new values are quite significant as can be documented on the example of the Be star LQ And. Percy (1983) reported periodic light variations of this B 3–4e star with a period of 0·31 days and argued that this period is too short to be the rotational period of the star, referring to the mean masses and radii compiled by Underhill. A brief inspection of Tab. 4 shows that his conclusion is less certain with regard to the new data – a period of 0·3 days being at the margin of the rotational periods permitted for a B 4 main sequence star.

LQ And was the only Be star with a well-determined photometric period, which was considered too short to be the rotational period, all other well determined photometric periods of Be stars falling safely into the range of the permitted rotational periods – so the importance of the present finding is thus quite clear.

Yet another comment is interesting in this connection. I argued (Harmanec 1983, 1984) that the photometric variations of LQ And can be reconciled better on the assumption of a double-wave light curve with a period of 0·62 days. Note that the primary of the contact binary RZ Pyx, a B 4 star (see Tab. 1C) rotates synchronously with an orbital period of 0·656 days, a value remarkably close to my preferred value for LQ And. This may indicate (as expected) that the critical periods and break-up velocities in column "1·5 R" of Tab. 4 are closer to reality.

In any case, it is clear that Underhill's mean values of masses and radii should no longer be used.

6. Spin-Orbital Synchronization; Synchronization at Periastron Versus Pseudosynchronization

Hut (1981) has developed a concept of pseudosynchronization for binaries in eccentric orbits. He took into account the fact that the tidal interaction is strongest near periastron. For an exact synchronization *at* periastron, the observed projected rotational velocity $v_{PS} \sin i$ (in km s^{-1}) is given by

Table 4

Comparison of masses and radii of main-sequence B stars plus corresponding critical rotational velocities (in km s^{-1}) and periods (in days) compiled by Underhill (1982) with the data derived here.

Spectral class	Underhill (1982)							This paper						
	log T_{eff}	$M/M_\odot$	$R/R_\odot$	V_{crit}		P_{crit}		log $T_{eff}^{*)}$	$M/M_\odot$	$R/R_\odot$	V_{crit}		P_{crit}	
				R	$1{\cdot}5R$	R	$1{\cdot}5R$				R	$1{\cdot}5R$	R	$1{\cdot}5R$
B 0	4·488	16·8						4·475	14·57	5·80	692	565	0·425	0·779
B 0·5	4·466	14·3	8·2	577	470	0·720	1·322	4·455	13·19	5·46	679	554	0·407	0·748
B 1	4·430	10·4	6·8	540	441	0·637	1·171	4·418	11·03	4·91	654	534	0·380	0·698
B 1·5	4·410	13·6	6·3	642	524	0·497	0·913	4·391	9·73	4·57	637	520	0·364	0·667
B 2	4·358	10·3	6·0	572	467	0·531	0·975	4·364	8·62	4·28	620	506	0·349	0·642
B 2·5	4·309	10·4	5·2	618	504	0·426	0·783	4·322	7·20	3·88	594	486	0·331	0·606
B 3	4·268	8·8	5·1	574	468	0·450	0·827	4·280	6·07	3·56	571	466	0·315	0·580
B 4	4·213	6·8	4·7	525	429	0·453	0·832	4·235	5·12	3·26	547	447	0·302	0·554
B 5	4·181	5·5	4·7	472	386	0·504	0·925	4·190	4·36	3·01	525	429	0·290	0·533
B 6	4·138	4·7	4·5	446	364	0·510	0·938	4·149	3·80	2·81	508	415	0·280	0·515
B 7	4·113	5·0	3·9	494	404	0·399	0·733	4·112	3·38	2·65	493	403	0·271	0·500
B 8	4·076	3·9	3·6	454	371	0·401	0·736	4·063	2·91	2·44	476	389	0·259	0·476
B 9	4·038	2·4	3·1	384	314	0·408	0·750	4·015	2·52	2·25	462	377	0·247	0·453
B 9·5	4·009	2·6	2·7	429	350	0·319	0·586	3·995	2·38	2·17	457	373	0·241	0·441

*) After Popper (1980)

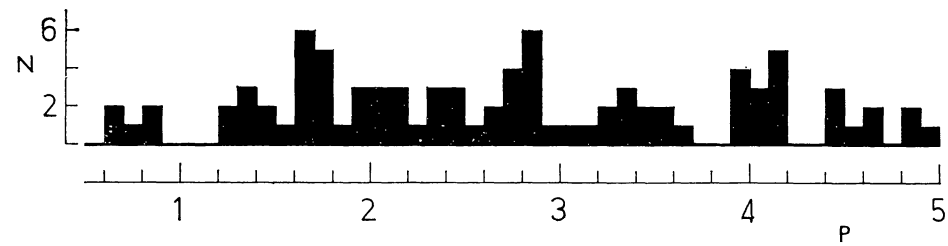

Fig. 5. A histogram of the orbital periods of eclipsing binaries from Tab. 1 and from Popper (1980) in the range from 0·6 to 5·0 days.

(7) $$v_{PS} \sin i = (1 + e)^2/(1 - e^2)^{3/2}\, v_S \sin i\,,$$
where
(8) $$v_S = 50{\cdot}615(R/R_\odot)/P$$
is the usual synchronous rotational velocity, e being the orbital eccentricity, P the orbital period (in days), and i the inclination of the rotational axis. Hut's pseudosynchronous rotational velocity (see his formula (42)) v_{PSEUDO} is smaller than v_{PS} given by (7) for all non-zero eccentricities, attaining the minimum value of $0{\cdot}799 v_{PS}$ for $e = 0{\cdot}308$ and being smaller than $0{\cdot}825 v_{PS}$ for all eccentricities larger than 0·16. To my surprise, the observed projected rotational velocities of most systems of Table 1 with non-zero eccentricities seem to indicate that synchronization at periastron, rather than pseudosynchronization, occurs for most of real binaries. Consequently, assuming coplanarity of rotational and orbital axes, I calculated synchronous and (in cases of non-zero eccentricity) at periastron synchronized projected rotational velocities for all systems of Tab. 1, for which the observed projected rotational velocities are available. I have also calculated the differences between the observed and calculated values expressed in the units of errors of the observed $v \sin i$ given by the original investigators (columns O−S, and O−PS of Tab. 1). If no error was given in the original paper, I assumed that the error was ten per cent of the value of $v \sin i$.

An inspection of Tab. 1 reveals that there is indeed a strong tendency to synchronous rotation for binaries with circular orbits, and to synchronization at periastron for binaries with larger orbital eccentricities (within the limits of about double the quoted errors of $v \sin i$). It is also clear that synchronous rather than at periastron synchronized rotation is observed in systems with orbits of low eccentricity (which seems natural considering that only small changes of the mutual attractive force of the components occur during the orbital motion in such systems), and for some late-type stars (c.f. primary of V 1143 Cyg, secondary of EK Cep, both components of AI Phe), which is not as apparent a result.

Indirectly, the generally good agreement of the observed and predicted (synchronized or at periastron synchronized) $v \sin i$ for the majority of stars supports the assumption that the rotational and orbital axes are indeed coplanar in most real binaries. There are, however, several strangers in Tab. 1, which seem to be in slower than synchronous rotation, and some OB stars with a high rate of angular rotation, many times exceeding the synchronous rate. Such objects deserve further detailed studies.

7. Miscellaneous Comments

A. *Preferred orbital periods*? When compilling the data of Tabs 1 and 2, I realized the frequent occurrence of certain values of the orbital periods. Figure 5 is a histogram of the orbital periods for the (most numerous) binaries with periods between 0·6 and 5 days. The binaries of Tab. 1 and from Popper (1980) were considered. It is indeed seen that there are certain preferred periods. There are, for instance, 11 systems (i.e. 12·5 per cent of the sample) with orbital periods between 1·6 and 1·8 days, 10 systems (11·4 per cent) with periods between 2·7 and 2·9 days or 12 systems (13·6 per cent) with periods between 3·9 and 4·2 days. The total sample of 88 systems was divided into 44 bins of 0·1 day in period. On the assumption of a homogeneous distribution, one would expect 2 systems (i.e. 2·3 per cent) per one bin, i.e. 4 systems between 1·6 and 1·8 days, 4 systems between 2·7 and 2·9 days, and 6 systems between 3·9 and 4·1 days. It is possible, in such a relatively small sample, that the apparent peaks in the period distribution are not statistically significant.

If real, they could be caused either by a different probability of discovery or by some physical cause (like spin-orbital resonances during formation, or evolution of the binaries in question). It is interesting to note that one of the systems with its orbital period close to 4 days is Spica, for which there is firm evidence of travelling bumps in the line profiles, which were interpreted as being due to non-radial pulsations with two modes, which are in resonance with the interior rotation rate, the orbital rate, and one another (Smith 1985).

Table 5

Mean and extreme observed absolute dimensions of Am stars

Spectral class	log T_{eff}	Mass			Radius			M_{bol}			
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	No.
A 2 m	3·943	1·78	2·20	1·95 (13)	1·52	2·49	1·87 (31)	2·00	0·88	1·61 (37)	3
A 3 m	3·932	1·98	2·01	2·00 (1)	2·02	2·13	2·09 (4)	1·65	1·36	1·55 (10)	3
A 5 m	3·911			1·98			1·89			1·83	1
A 7 m	3·890	1·8	2·1	1·91 (10)	1·89	3·0	2·36 (33)	2·03	1·02	1·61 (30)	3
A 8 m	3·875	1·62	2·00	1·79 (11)	1·58	2·50	1·99 (27)	2·69	1·52	2·13 (34)	3
A 9 m	3·859			1·63			1·88			2·34	1
F 0 m	3·844	1·78	1·81	1·80 (2)	2·20	2·20	2·20 (0)	2·15	2·12	2·14 (2)	2

All masses and radii are in solar units.

B. *The metallic-line stars* Table 5 summarizes the masses, radii and bolometric magnitudes of Am stars. Their effective temperatures (and inferred spectral types) are usually based on their observed photometric colours. It is interesting to note that the mean observed masses and radii of Am stars decline only little along the observed spectral range from A2m to F0m. It is even conceivable that these quantities (radii in particular) are nearly the same for all spectral subclasses. The mean values over all Am stars considered here are $M = 1{\cdot}885\ M_{\odot}$ and $R = 2{\cdot}069\ R_{\odot}$, which corresponds to a normal A 4·5 star in mass but an A 2 star in radius.

C. *Subgiants and giants* No attempt is made here to define some mean parameters for the stars above the main sequence. This is because the available sample contains many semi-detached and contact binaries, for which the radii of component stars are determined by the binary orbital period and mass ratio. Such stars can have different masses depending on the evolutionary stage of the system. In any case, the relevant information can be found in Tab. 1. It is notable that the parameters of stars in some early--type semi-detached or contact systems do not differ too much from the mean relations (3).

D. *The Sun* Taken at face value, the relations defined here qualify the Sun as slightly undersized and undermassive for its effective temperature but the significance of this result is not clear. Note also that Popper's scale of effective temperatures would qualify the Sun as a G 5 star.

Acknowledgments

I am very obliged to Drs J. Andersen, S. A. Bell, R. Haefner, R. W. Hilditch, G. Hill, C. H. Lacy and D. M. Popper, who kindly sent me copies of their series of papers on absolute dimensions and references to some other papers on accurate masses and radii of stars, which were vital for this study. Valuable comments of Dr. P. Hadrava and Dr. M. Ouhrabka are also acknowledged.

REFERENCES

Andersen J. 1983 *Astron. Astrophys.* **118**, 255

Andersen J., Giménez A. 1985 *Astron. Astrophys.* **145**, 206

Andersen J., Gronbech B. 1975 *Astron. Astrophys.* **45**, 107

Andersen J., Vaz L. P. R. 1984 *Astron. Astrophys.* **130**, 102

Andersen J., Nordström B., Wilson R. E. 1980 *Astron. Astrophys.* **82**, 225

Andersen J., Clausen J. V., Nordström B., Reipurth B. 1983a *Astron. Astrophys.* **121**, 271

Andersen J., Clausen J. V., Giménez A., Nordström B. 1983b *Astron. Astrophys.* **128**, 17

Andersen J., Clausen J. V., Nordström B. 1984a *Astron. Astrophys.* **134**, 147

Andersen J., Clausen J. V., Nordström B. 1984b *Astron. Astrophys.* **137**, 281

Andersen J., Clausen J. V., Nordström B., Popper D. M. 1985 *Astron. Astrophys.* **151**, 329

Andersen J., Garcia J. M., Giménez A., Nordström B. 1987a *Astron. Astrophys.* **174**, 107

Andersen J., Clausen J. V., Nordström B. 1987b *Astron. Astrophys.* **175**, 60

Andersen J., Clausen J. V., Gustafsson B., Nordström B., VandenBerg D. A. 1988 *Astron. Astrophys.* **196**, 128

Bell S. A., Malcolm G. J. 1987a *Monthly Notices Roy. Astron. Soc.* **226**, 899

— 1987b *Monthly Notices Roy. Astron. Soc.* **227**, 481

Bell S. A., Hilditch R. W., Adamson A. J. 1986 *Monthly Notices Roy. Astron. Soc.* **223**, 513

Bell S. A., Adamson A. J., Hilditch R. W. 1987a *Monthly Notices Roy. Astron. Soc.* **224**, 649

Bell S. A., Hilditch R. W., Adamson A. J. 1987b *Monthly Notices Roy. Astron. Soc.* **225**, 961

Bell S. A., Kilkenny D., Malcolm G. J. 1987c *Monthly Notices Roy. Astron. Soc.* **226**, 879

Clausen J. V., Nordström B. 1980 *Astron. Astrophys.* **83**, 339

Clausen J. V., Giménez A., Scarfe C. 1986 *Astron Astrophys.* **167**, 287
Haefner R., Skillen I., deGroot M. 1987 *Astron. Astrophys.* **179**, 141
Harmanec P. 1983 *Hvar Obs. Bull.* **7**, 55
— 1984 *Bull. Astron. Inst. Czechosl.* **35**, 193
Helt B. E. 1987 *Astron. Astrophys.* **172**, 155
Hilditch R. W. 1984 *Monthly Notices Roy. Astron. Soc.* **211**, 943
Hilditch R. W., Bell S. A. 1987 *Monthly Notices Roy. Astron. Soc.* **229**, 529
Hilditch R. W., Lloyd Evans T. 1985 *Monthly Notices Roy. Astron. Soc.* **213**, 75
Hilditch R. W., Skillen I., Carr D. M., Aikman G. C. L. 1986 *Monthly Notices Roy. Astron. Soc.* **222**, 167
Hill G., Batten A. H. 1984 *Astron. Astrophys.* **141**, 39
Hut P. 1981 *Astron. Astrophys.* **99**, 126
Lacy C. H., Frueh M. L. 1985 *Astrophys. J.* **295**, 569
— 1987 *Astron. J.* **94**, 712
Li Y. - F., Leung K. - C. 1985 *Astrophys. J.* **298**, 345
Lines H. C., Lines R. D., Guinan E. F., Robinson C. R. 1986 *Inf. Bull. Var. Stars* 2932
Percy J. R. 1983 *Astron. J.* **88**, 427
Plavec M. J., Dobias J. J. 1987 *Astron. J.* **93**, 440
Popper D. M. 1980 *Ann. Rev. Astron. Astrophys.* **18**, 115
— 1981 *Astrophys. J.* **244**, 541
— 1982a *Astrophys. J.* **254**, 203
— 1982b *Astrophys. J.* **262**, 641
— 1987a *Astrophys. J.* **313**, 81
— 1987b *Astron. J.* **93**, 672
Popper D. M., Andersen J., Clausen J. V., Nordström B. 1985 *Astron. J.* **90**, 1324
Popper D. M., Lacy C. H., Frueh M. L., Turner A. E. 1986 *Astron. J.* **91**, 383
Schneider D. P., Leung K. - C. 1978 *Astrophys. J.* **223**, 202
Smith M. A. 1985 *Astrophys. J.* **297**, 206
Stoeckley T. R., Buscombe W. 1987 *Monthly Notices Roy. Astron. Soc.* **227**, 801
Straižys V., Kuriliene G. 1981 *Astrophys. Space Sci.* **80**, 353
Tomkin J. 1978 *Astrophys. J.* **221**, 608
Tomkin J., Popper D. M. 1986 *Astron. J.* **91**, 1428
Underhill A. B. 1982 in *B Stars With and Without Emission Lines*, Ed. by A. Underhill and V. Doazan, NASA/CNRS SP-456 Monograph, pp. 36—37 and 60
Vaz L. P. R., Andersen J. 1984 *Astron. Astrophys.* **132**, 219
Wachmann A. A., Popper D. M., Clausen J. V. 1986 *Astron. Astrophys.* **162**, 62

THEORETICAL EMISSION LINE PROFILES IN THE SPECTRA OF ACTIVE GALACTIC NUCLEI

P. Hadrava[1]), Anna S. Zentsova[2])

[1]) *Astronomical Institute, Czechoslovak Academy of Sciences, 251 65 Ondřejov, Czechoslovakia*
[2]) *Visitor from the A. F. Ioffe Physical and Technical Institute, U.S.S.R. Academy of Sciences, Leningrad, U.S.S.R.*

Received 31 March 1988

ТЕОРЕТИЧЕСКИЕ ПРОФИЛИ ЭМИССИОННЫХ ЛИНИЙ В СПЕКТРАХ ЯДЕР АКТИВНЫХ ГАЛАКТИК

Рассмотрено истечение газа из ядра активной галактики в виде ветра при учете его нагрева коротковолновим излучением центрального источника. Предполагается, что эмиссионные облака возникают в этом газе в результате развития в нем тепловой неустойчивости. Исследовано движение этих облаков во внутренней зоне оболочек ядер под действием сил светового давления, трения, действующего на облако при его движении относительно межоблачного газа, и гравитационного притяжения к центральному объекту. Выполнен рассчет профилей водородных линий формирующихся в облаках. Рассмотрены случаи движения эмиссионных облаков внутри телесного угла Ω при $\Omega \sim 1$ и $\Omega \ll 1$.

The gas outflow from an active galaxy nucleus is modelled by the stellar wind driven by short wavelength radiation of the central source. The emission clouds are assumed to arise in this gas due to its thermal bistability. The motion of emission clouds is calculated in the inner zone of the nucleus envelope. The radiative pressure, friction due to the relative motion of the cloud with respect to the confining gas and the gravitation of the central body are taken into account. The line profiles of the hydrogen lines radiated by the clouds are computed for both cases of the narrow stream ($\Omega \ll 1$) and their motion inside a wide cone ($\Omega \sim 1$).

Key words: active galactic nuclei — Compton driven wind — line profiles