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# SPECTROSCOPIC BINARIES AND COLLAPSED STARS\*

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# ABSTRACT

Lists are given of single-line, spectroscopic binaries with large mass functions. The absence of a secondary spectrum in these systems could, in principle, result from the secondary star's being either a collapsed star or a massive neutron star. For all these systems, however, other explanations are possible in the light of present observations. Statistical considerations suggest that few, if any, of the systems in these lists contain collapsed or neutron-star secondaries. None of these binary systems coincide with any published X-ray source position.

# I. NON-ECLIPSING, SINGLE-LINE BINARIES WITH LARGE MASS FUNCTIONS

Theoretical considerations suggest that some massive stars should terminate their evolution by gravitational collapse (see, e.g., Wheeler 1966; Thorne 1967). The end products of such collapse—"neutron stars" of  $\mathfrak{M} \leq 1.5 \mathfrak{M}_{\odot}$ , and "collapsed stars" of  $\mathfrak{M} \geq 1.5 \mathfrak{M}_{\odot}$ —have never been observed and, indeed, should be virtually impossible to observe directly because of their small size.

Zel'dovich and Guseynov (1965) have proposed that collapsed stars and neutron stars might be found among the unseen companion stars of single-line spectroscopic binaries. Motivated by this suggestion, we have searched the *Sixth Catalogue of the Orbital Elements of Spectroscopic Binary Systems* (Batten 1968) for systems which could harbor collapsed or neutron-star secondaries. The results of this search are contained in Tables 1 and 2, which extend a table of seven systems given by Zel'dovich and Guseynov (1965).

Our search of the binary catalogue followed the procedure of Zel'dovich and Guseynov. For each system, the mass,  $\mathfrak{M}_1$ , of the primary star was estimated from its spectral type; and an approximate lower limit,  $\mathfrak{M}_{2 \min}$ , to the mass of the unseen companion was then calculated from the observed mass function,  $f(\mathfrak{M}) = \mathfrak{M}_2^3 \sin^3 i/(\mathfrak{M}_1 + \mathfrak{M}_2)^2$ , using  $\sin i = 1$  (orbit seen edge-on).

The systems divide into three classes. Class I systems, in which the minimum mass of the unseen star is less than the Chandrasekhar limit  $(1.4 \mathfrak{M}_{\odot})$ , are of little interest to the search for collapsed and neutron stars since the unseen companion may well be a white dwarf.

The class II systems, in which the unseen secondary star is larger than  $1.4 \mathfrak{M}_{\odot}$  but is less massive than the primary star, are listed in Table 1. For most of the class II systems the difference between the primary and the secondary mass is rather large, so that the secondary is probably too dim for its lines to have been detected on the available spectrograms. Of the four systems in which the two stars have similar masses (nos. 2, 6, 18, and

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TABLE 1\*

# SINGLE-LINE BINARIES OF CLASS II

 $(\mathfrak{M}_1 > \mathfrak{M}_2 \min \ge 1.4\mathfrak{M}_{\odot})$ 

BH-T. $0$ (Gas $01467$ , $0$ (Gas $001467$ , $1014$ (G) $114$ , $1202$ $116$ <	No.	Star	Q 1900	Ô1900	Magnitude	Spectral Type	Period (days)	v	$K_1$ (km sec <sup>-1</sup> )	f(M)	$\frac{\mathfrak{M}_1}{\mathfrak{M}_{\odot}}$	$\frac{\mathfrak{M}_{\imath\mathrm{min}}}{\mathfrak{M}_{i}\odot}$
BistHit YooG33H-34H5FAM2 <td>B47</td> <td>ω Cas Cet</td> <td>01 h48m2 02 30 5</td> <td><math>+68^{\circ}12'</math> + 0 47</td> <td>4.99 4.28</td> <td>B8 F0 TV</td> <td>69.92 1202 2</td> <td>0.30 460</td> <td>29 64 14 4</td> <td>0.164</td> <td>4.5</td> <td>1.9</td>	B47	ω Cas Cet	01 h48m2 02 30 5	$+68^{\circ}12'$ + 0 47	4.99 4.28	B8 F0 TV	69.92 1202 2	0.30 460	29 64 14 4	0.164	4.5	1.9
B100. 17 Tau 03 0 + 13 8 6.0 H 00 46 H 20 114 6.0 114 13 115 7 10 114 13 10 5 V 148 5 10 0 114 10 114 13 10 5 V 148 5 10 0 114 13 15 11 18 115 15 10 10 114 13 10 5 V 148 5 10 0 117 10 110 10	B87	HR 976	03 09.8	+34 19	6.24	A2m	5.54348	.038	62.0	0.137	3.0	1.4
BIJV: $\mu$ FFT 04 015 121 105 14 FT 04 10 15 12 V 165 10 17 105 13 05 13 11 15 13 105 15 14 15 15 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 19 18 15 18 18 18 11 18 15 18 18 10 11 14 13 01 18 14 19 11 14 13 01 18 18 11 16 15 18 18 12 16 18 18 11 16 15 18 18 12 16 18 18 11 16 15 18 18 12 18 18 12 18 18 11 18 18 12 18 18 18 12 18 18 18 12 18 18 18 18 12 18 18 18 12 18 18 18 18 18 18 18 18 18 18 18 18 18	B100	17 Tau	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	+23 48	3.69	B6 III	100.46	.522	26.0	0.114	0.9	1.9
B135 $0.3$ Tau $05$ 52.0 $+14$ 68 $5.4$ $12^{\circ}$ V $15^{\circ}$ 11 $17.5$ $12^{\circ}$ 12 $14^{\circ}$ 33B175 $7$ Ori A abc $05$ 30.2 $+23$ 07 $5.47$ $10^{\circ}$ T $10^{\circ}$ T $0.56$ $2^{\circ}$ 7 $1^{\circ}$ 7B175 $7$ Ori A abc $05$ 30.2 $+23$ 07 $5.47$ $10^{\circ}$ T $2^{\circ}$ 11 $17.5$ $10^{\circ}$ 13 $0.56$ $2^{\circ}$ 8 $16^{\circ}$ B135 $7$ Ori $05$ 30.3 $+42$ 08 $5.47$ $10^{\circ}$ 7 $5.47$ $10^{\circ}$ 7 $2^{\circ}$ 1 $10^{\circ}$ 7 $2^{\circ}$ 8 $10^{\circ}$ 7B136 $07$ 10 $05$ 31.1 $+16$ 21 $0.55$ 1 $5.47$ $0.57$ 1 $2^{\circ}$ 1 $13^{\circ}$ 0.56 $2^{\circ}$ 1 $14^{\circ}$ B234 $07$ 25.3 $-23$ 1 $13^{\circ}$ 6 $0.91$ 1 $17^{\circ}$ 11 $17^{\circ}$ 11 $17^{\circ}$ 3 $0.56$ 25 $8^{\circ}$ 8B242 $e^{\circ}$ Pup $07$ 35.3 $-44$ 3 $3^{\circ}$ 5 $10^{\circ}$ 16 $17^{\circ}$ 11 $10^{\circ}$ 5 $2^{\circ}$ 14B234 $e^{\circ}$ Pup $07$ 55.3 $-23$ 3 $15^{\circ}$ 11 $17^{\circ}$ 11 $17^{\circ}$ 11 $17^{\circ}$ 3 $10^{\circ}$ 5B234 $e^{\circ}$ Pup $07$ 55.3 $10^{\circ}$ 57 $10^{\circ}$ 57 $10^{\circ}$ 57 $10^{\circ}$ 57 $20^{\circ}$ 20 $20^{\circ}$ 20B234 $e^{\circ}$ Pup $07$ 55.1 $25^{\circ}$ 11 $116^{\circ}$ 17 $10^{\circ}$ 55 $10^{\circ}$ 5 $10^{\circ}$ 5 $20^{\circ}$ 5B234 $e^{\circ}$ Pup $07$ 55 $10^{\circ}$ 7 $10^{\circ}$ 7 $10^{\circ}$ 7 $10^{\circ}$ 7 $20^{\circ}$ 20 </td <td>B117.</td> <td>μ Per</td> <td>04 07 6</td> <td>+48 09</td> <td>4.14</td> <td>GO Ib</td> <td>285.272</td> <td>200</td> <td>20.07</td> <td>0.25</td> <td>10. • •</td> <td>о. г и</td>	B117.	μ Per	04 07 6	+48 09	4.14	GO Ib	285.272	200	20.07	0.25	10. • •	о. г и
BI711 $7$ Ori A abc $63$ $92$ $11$ $175$ $1.84$ $30$ $165$ $16$ $175$ $1.84$ $30$ $166$ $17$ $75$ $1.84$ $30$ $166$ $17$ $75$ $116$ <t< td=""><td>B150.</td><td>p 1au 103 Tau</td><td>05 02 0</td><td>+14 30 +24 08</td><td>5.41 5.41</td><td>B2 V</td><td>±00.3 58.31</td><td>189</td><td>36.73</td><td>0.28</td><td>12.</td><td>4.2</td></t<>	B150.	p 1au 103 Tau	05 02 0	+14 30 +24 08	5.41 5.41	B2 V	±00.3 58.31	189	36.73	0.28	12.	4.2
B175 $\chi$ Aur         65 $\chi$ Aur $\chi$ A	B171†	$\eta$ Ori A abc	05 19 4	- 2 29	3.32	B0.5 V	9.2 yr	-:	17.5	1.84	30.	16.
B184 $\phi$ Or $\phi$ O	B175 .	X Aur 371 O≓	05 26.2	+32 07	4.77	B5 Iab B0 IV	655.16 8 4 ur	171	20.53	0.56	25 17	9.6 2
B195         III partial provided for the properture predited provided for the properture provided for the pr	B184	lori B <sup>2</sup> Ori	05 30.5	-05 29	5.07	09.5 Vp	21.0315	.131	105.8	2.50	20.	14.
B244.       B0 r C.Ma       07       15.3       -124       4.45       0.10       -20       4.45       0.10       20	. B195	HD 40005	05 51.1	$+16\ 21$	6.91	B3 V	3.306	0	12	0.157	10.	30
B227. $e^{\text{Pup}}$ $07$ $261$ $-43$ $66$ $3.23$ $K5$ III $257.8$ $17$ $164.5$ $3.2$ $257.8$ $17$ $164.5$ $3.2$ $227.8$ $11.8$ $0.35$ $3.2$ $2$	. B234  B241	30 7 CMa HD 50543	07 14.5	-24 4/ -13 46	4.48 6 04	C9 III R5	124.90	0 <u>5</u> .5	49.5 45.6	0 10	20. 7 0	12. 2 0
B256.a Pup b 201007 48.8 -54 35-40 19 -54 353.73 -54 35G5 III -164 512660.411.8 -650.35 -3.23.22 -2.22.29 -2.22.29 -2.22.29 -2.22.20 	B242.	a Pup	07 26.1	-43 06	3.23	K5 III	257.8	.17	18.55	0.164	20	2.0
B297K Vet a Dra0.17 b 14 01.7-34 53 b 41 c Sco2.47 b 14 01.70.210 b 36.40.210 b 31.40.210 b 31.410.05 b 60.469 b 16.00.456 b 45.51.5 b 2.7 b 31.20.210 b 31.50.210 b 31.40.469 b 45.53.5 b 31.50.210 b 31.40.469 b 45.53.5 b 31.50.210 b 31.50.212 b 31.50.2120 b 31.50.2583 b 41.14.1 b 2.72.2 b 31.52.35 b 31.50.0112 b 31.51.5 b 31.50.150 b 31.40.469 b 31.41.5 b 31.51.10 b 31.41.10 b 31.51.10 b 31.61.10 b 31.51.10 b 31.61.10 b 3	B256.	a Pup	07 48.8	-40 19	3 73	G5 III	2660.	4,5	11.8	0.35	3.2	2.7 7.7
B444. $B.0145849$ 16 08.1 $+36$ 415.51 $K5, gK4$ $2150.$ $6$ $16.0$ $0.469$ $4.5$ $3.0$ B444. $\sigma$ Sco16 15 1 $-25$ 212.89B1 III $34.2$ $36.122$ $0.220$ $0.112$ $15.0$ $3.4$ B546. $\beta$ Lyr $18$ 11 $10.1$ $+14.30$ $5.31$ $60$ 11 $34.2$ $36.122$ $0.2583$ $4.1$ $2.2$ B540. $\beta$ Lyr $18$ 13 $-451$ $4.21$ $25.8$ $33.35$ $35.7$ $0.220$ $36.122$ $0.2583$ $4.1$ $2.2$ B540. $\beta$ Lyr $18$ 36.2 $+3651$ $5.51$ $B3$ $83.352$ $37$ $39.7$ $0.223$ $10$ $4.9$ B568.HD 176318 $18 5.02$ $+3651$ $5.01$ $B6$ $5.02$ $13.3$ $5.02$ $1.9$ B568.HD 184308/9 $19$ 27.3 $-4015$ $5.70$ $B6$ $2.725$ $0.93$ $10$ $4.9$ B568.HD 184308/9 $19$ 27.3 $-4015$ $5.70$ $A.625$ $0.33$ $5.022$ $4.0$ $11.6$ B568.HD 184308/9 $19$ 27.3 $-4015$ $5.70$ $A.625$ $0.32$ $0.33$ $5.0217$ $0.220$ B568.HD 184308/9 $19$ 27.5 $2.045$ $5.0211$ $108.5707$ $2.46$ $0.1202$ $0.217$ $10.6$ B568.HD 191473 $20.11.2$ $2.577-702$ $5.675$ $0.957$ $2.46$ $0.1222$ $1.9$ $1.6$ B501. $22.11$ $0.055$ <	. B297 .	k Vel 2 Dro	0 7 10 11 1	- 54 55 - 54 55	2.49	B2 IV A0 TTT	51 47	38	40.3 46.0	1.10 0.436	.11. 3.5	- c . r
$\overrightarrow{B444}$ $\sigma$ Sco16151 $-25$ 212.89BI III34.23634.0001121503.4 $\overrightarrow{B444}$ $\overrightarrow{a}$ $\overrightarrow{B416}$ $\overrightarrow{B}$ 1710 $\overrightarrow{1}$ $\overrightarrow{144}$ 305.39G0 II-III $\overrightarrow{51.578}$ $\overrightarrow{36.122}$ 0 $2533$ $4.1$ 2.2 $\overrightarrow{B544}$ $\overrightarrow{B544}$ $\overrightarrow{B117}$ 18 $\cancel{4.21}$ $\overrightarrow{65}$ $\cancel{5.39}$ $\overrightarrow{60}$ $\overrightarrow{127}$ $\overrightarrow{0.2583}$ $4.1$ 2.2 $\overrightarrow{B544}$ $\overrightarrow{B117}$ $\overrightarrow{851}$ $\overrightarrow{5.51}$ $\overrightarrow{B3}$ $\overrightarrow{83.352}$ $\overrightarrow{37}$ $\overrightarrow{397}$ $\overrightarrow{0.233}$ $\overrightarrow{10}$ $\cancel{4.19}$ $\overrightarrow{B568}$ $\overrightarrow{HD176318}$ $\overrightarrow{18}$ $\overrightarrow{5.90}$ $\overrightarrow{A3111}$ $\overrightarrow{83.352}$ $\overrightarrow{36.122}$ $\overrightarrow{0.523}$ $\overrightarrow{10}$ $\cancel{4.9}$ $\overrightarrow{B568}$ $\overrightarrow{HD184398/9}$ $\cancel{19}$ $\cancel{27.3}$ $-4015$ $\overbrace{5.90}$ $\overrightarrow{A3111}$ $\cancel{4.625}$ $\overrightarrow{09}$ $\overrightarrow{0.150}$ $\overrightarrow{5.0}$ $\cancel{4.9}$ $\overrightarrow{B568}$ $\overrightarrow{HD19473}$ $201$ $\cancel{22.3}$ $\overrightarrow{10}$ $\cancel{4.55}$ $\overrightarrow{10}$ $\overrightarrow{4.1}$ $\cancel{2.2}$ $\overrightarrow{B506}$ $\cancel{10}$ $\overbrace{537}$ $\overrightarrow{50}$ $\overrightarrow{3.1}$ $\cancel{4.655}$ $\overrightarrow{0.25}$ $\overrightarrow{0.15}$ $\overrightarrow{0.25}$ $\overrightarrow{4.0}$ $\overrightarrow{1.6}$ $\overrightarrow{B506}$ $\overrightarrow{10}$ $\overrightarrow{525}$ $\overrightarrow{10}$ $\overrightarrow{52.5}$ $\overrightarrow{09}$ $\overrightarrow{52.5}$ $\cancel{4.0}$ $\overrightarrow{52.5}$ $\overrightarrow{4.0}$ $\overrightarrow{1.6}$ $\overrightarrow{B506}$ $\overrightarrow{22}$ $\overrightarrow{10}$ $\overrightarrow{22.5}$ $\overrightarrow{00}$ $\overrightarrow{22.5}$ $\overrightarrow{0.26}$ $\overrightarrow{0.26}$ $\overrightarrow{2.2}$ $$	B442	HD 145849	15 08.1	+36 41	5.51	K5. gK4	2150.	0.0	16.0	0 469	4 .5	3.0
B476       a Her B       17       10       +14       30       5.39       G0 II-III       51.578       .0220       36.122       0.5533       4.1       2.7         B528 $\beta$ Sct       18       41.9       -4       51       5.51       B3       38.352       .35       16.65       0.533       50       2.7         B544       HD 176318       18       50.2       +36       51       5.51       B3       88.352       .37       37       0.533       50       2.7         B567       HD 184308/9       19       27.3       -40       15       6.37       K2 II-III       4.9       50       70.5       0.53       10.55       6.0       3.4       19       27.5       0.18       3.0       10.6       50       11.9       4.9         B566       HD 191473       20       5.17       G2 Ib       570       72.5       0.18       3.0       10.6       3.4       10.6       3.4       10.6       3.4       10.16       3.4       10.5       3.4       10.5       3.4       10.5       3.4       10.5       3.4       10.5       3.4       10.5       3.6       3.4       10.5       3.4       10.5<	B444.	or Sco	16 15 1	-25 21	2.89	BI ÍÍÍ	34.2	.36	34.0	0 112	15 0	3.4
B528. $\beta$ Sct 18 41.9 $-4.51$ 5.51 63.1 63.11 83.32 10.05 0.33 50 2.7 10.52 10.52 10.53 10 2.7 18 5.5 1854. 18 5.2 $+36$ 7.5 19 5.7 10 5.7 10 5.7 10 5.5 10 5.0 1.9 27.3 19 27.3 $-40$ 15 5.7 10 5.7 10 5.8 3.32 10.5 10 5.0 1.9 27.3 10 2.7 10 5.7 10 5.6 1.5 10 5.0 1.0 10.5 5.0 1.0 5.7 10 5.8 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5	B476	a Her B	17 10 1	+14 30	5.39	G0 II-III	51.578	.0220	36.122	0.2583	4.1	2.2
B540. ${}^{91}$ Lyr 18 50.2 $+30$ 51 5.01 B5 70 B6 V 2.91225 169 70.3 0.150 5.0 1.9 27.3 $-40$ 15 5.90 A3 III 4.625 0.9 79.3 0.150 5.0 1.0 1.6 B5 6.37 1.0 1.6 B5 70 1.9 27.3 $-40$ 15 5.90 A3 III 1.6 18.570 0.9 79.3 0.150 5.0 1.0 1.6 B5 6.2 1.0 10.5 Sge 10.5 1.5 $+16$ 22 5.87-7 02 F6-65 Ib 6.5 V 4.2876 0.447 10.5 4.2 15 0.3 0.1222 4.0 1.6 1.6 B5 6.2 10.101 191473 2.0 15.5 $+16$ 22 5.17 02 F6-65 Ib 6.70 $-246$ 15 0.37 $-326$ 10 $-222$ 1.0 $-223$ 1.0 $-236$ 1.0 $-336$ 1.0 $-336$ 1.0 $-366$ 1.	B528.	$\beta$ Sct	18 41.9	- 4 51	4.21	G5 II	834.	ŝ	10.05	0.33	ۍ د 0	2.7
* The entres in this table include all single-line, non-eclipsing binaries listed in Batten's       * The entres in this table include all single-line, non-eclipsing binaries listed in Batten's       * The column $\mathfrak{M}_1/\mathfrak{M}_2$ $\mathfrak{M}_2/\mathfrak{M}_2$ <	B540.	8 <sup>1</sup> Lyr HD 176218	18 50.2 18 51 6	+30.51	10.0	B3 B6 V	28.352 2 01225	.3/ 160	39 / 70 3	0.523	10. 2 U	4.9
B568.       HD 184398/9       19 29.2 $+55$ 31 $6.37$ $K2$ II-III       108.5707 $054$ $22.1$ $0.1222$ $4.0$ $1.6$ B5804.       HD 184398/9       19 51.2 $+165$ 31 $6.37$ $F6-G5$ Ib $6.62$ $22.1$ $0.1222$ $4.0$ $1.6$ $3.4$ B5804.       HD 191473       20 05 0 $+3657$ $5.87-7$ 02 $F6-G5$ Ib $676.2$ $2246$ $15$ 03 $0.217$ $10$ $3.4$ B501.       22 Vul       20 05 0 $+3657$ $5.17$ $622$ Ib $5.51.0$ $050$ $26.8$ $0.50$ $10$ . $3.4$ B601.       22 Vul       20 11.2 $+23$ 12 $5.17$ $G2$ Ib $251.0$ $050$ $26.8$ $0.50$ $10$ . $4.8$ $6.2$ $8001.$ 22 Vul $20 11.2$ $+23$ 12 $5.17$ $G2$ Ib $251.0$ $050$ $26.8$ $0.50$ $10$ . $4.8$ $6.2$ $8001.$ $22$ Vul $20 10.2$ $6.2$ Ib $251.0$ $050$ $26.8$ $0.50$ $10$ . $4.8$	B567	201 G Sor	10 27 3	-40 15	00 2	A3 TIT	4 625	ĝ	2.02	0.18	) (C ) (C ) (C	1.0
BS01.10 Sige19 51.5+16 22 $5.87-7$ 02 $F6-G5$ Ib $676.2$ $246$ 15 030.21710. $3.4$ B501.22 Vul20 05 0+36 57 $8.6$ $B0.5$ V $4.2876$ $0447$ $106.48$ $0.535$ $15$ $6.2$ B501.22 Vul20 11.2+23 12 $5.17$ $G2$ Ib $251.0$ $050$ $26.8$ $0.535$ $15$ $6.2$ * The entries in this table include all single-line, non-eclipsing binaries listed in Batten's actuality for which $\mathfrak{M}_1 > \mathfrak{M}_2$ is our estimate of the mass of the pinary star, based on its spectral type. The column $\mathfrak{M}_1/\mathfrak{M}_{\odot}$ is a lower limit on the mass of the pinary star, based on its acture yielded no convincing evidence (ez. 4 obublies) for the presence of a normal which is obtained from the mass function, $f(\mathfrak{M})$ , using our estimated primary mass, $\mathfrak{M}_1$ , and one survey of the literature, we have adopted different spectral type. The column $\mathfrak{M}_2/\mathfrak{M}_{\odot}$ is a lower limit on the mass of the secondary star, based on its secondary star, based on its secondary star, based on its secondary star. As a result of our survey of the literature, we have adopted different spectral type. The column $\mathfrak{M}_2/\mathfrak{M}_{\odot}$ is a lower limit on the mass of the secondary star, based on its secondary star. As a result of our survey of the literature, we have adopted different spectral type. The column $\mathfrak{M}_2/\mathfrak{M}_{\odot}$ is a lower limit on the mass of the secondary star, based on its secondary star. As a result of our survey of the literature, we have adopted different spectral type. The column $\mathfrak{M}_2/\mathfrak{M}_{\odot}$ is a lower limit on the mass of the secondary star. Secondary star, based on its secondary star. As a result of our survey of the literature, we have adopted different spectral type. The column $\mathfrak{M}_2/\mathfrak{M}_{\odot}$ is a lower li	B568	HD 184398/9	19 29.2	+55 31	6.37	K2 II-III	108.5707	054	22.1	0.1222	4.0	1.6
B596   HD 191473 20 05 0 +36 57 8.6 B0.5 V 4.2876 0447 106.48 0.535 15 6.2 B601 22 Vul 22 Vul 2011.2 +23 12 5.17 G2 Ib 251.0 050 26.8 0.50 10. 4.8 * The entres in this table include all single-line, non-eclipsing binaries listed in Batten's number. The column $\mathfrak{M}/\mathfrak{M} \odot$ is our estimate of the mass of the primary star, based on its (88) catalogue, for which $\mathfrak{M}_1 > \mathfrak{M}_2 \odot$ is a lower limit on the mass of the secondary star, rather start spectral uses for the presence of a normal which is obtained from the mass function, $\mathfrak{M}/\mathfrak{M} \odot$ is a lower limit on the mass of the secondary star, rather start spectral uses for the presence of a normal which is obtained from the mass function, $\mathfrak{M}/\mathfrak{M} \odot$ is a lower limit on the mass of the secondary star, rather start spectral uses for the presence of a normal using sin $i = 1$ (orbit seen edge-on). The remaining notation and entries are those of Batten.	B580‡.	10 S Sge	19 51.5	$+16\ 22$	5.87-7 02	F6-G5 Ib	676.2	.246	15 03	0.217	10.	3.4
* The entries in this table include all single-line, non-eclipsing binaries listed in Batten's number. The column $\mathfrak{M}_1/\mathfrak{M}_{\odot}$ is our estimate of the mass of the primary star, based on its (68) catalogue, for which $\mathfrak{M}_1 > \mathfrak{M}_2$ , $\mathfrak{M}_2 > \mathfrak{M}_2$ ) is our estimate of the mass of the primary star, based on its rature yielded no convincing evidence (e.g., doubling of lines) for the presence of a normal which is obtained from the mass function, $f(\mathfrak{M})_1$ , using our estimated primary mass, $\mathfrak{M}_1$ , and dary star, and for which our own survey of the spectral uses in a formal which is obtained from the mass function, $f(\mathfrak{M})_1$ , using our estimated primary mass, $\mathfrak{M}_1$ , and out own survey of the interactive the primary star spectral uses in a restrict the restrict on the mass function, $f(\mathfrak{M})_1$ , using our estimated primary mass, $\mathfrak{M}_1$ , and out own to the primary mass, $\mathfrak{M}_1$ , and out the primary star start. As a result of our survey of the filterature theore of a normal using sin $i = 1$ (orbit seen edge-on). The remaining notation and entries are those of Batten.	. B596	HD 191473	20 05 0	+3657	9.0 1	B0.5 V	4.2876	0447	106.48	0.535	15	6.5 •
* The entries in this table include all single-line, non-eclipsing binaries listed in Batten's number. The column $\mathfrak{M}_1/\mathfrak{M}_0$ is our estimate of the mass of the primary star, based on its 1.4 $\mathfrak{M}_0$ , and for which our own survey of the spectral type. The column $\mathfrak{M}_2$ mm/ $\mathfrak{M}_0$ is a lower limit on the mass of the secondary star, 6.8), each of the presence of a normal which is obtained from the mass function, $f(\mathfrak{M})$ , using our estimated primary mass, $\mathfrak{M}_1$ , and ondary star. As a result of our survey of the literature, we have adopted different spectral using sin $i = 1$ (orbit seen effecton), $f(\mathfrak{M})$ , using our estimated primary mass, $\mathfrak{M}_1$ , and ondary star. As a result of our survey of the literature. Since references to the literature $1 + 1$ using $i = 1$ (orbit seen effecton), $f(\mathfrak{M})$ , using our estimated primary mass, $\mathfrak{M}_1$ , and ondary star. As a result of our survey of the literature, we have adopted different spectral using $i = 1$ (orbit seen effecton), $f(\mathfrak{M})$ , using our estimated primary mass, $\mathfrak{M}_1$ , and mass $i = 1$ (orbit seen effecton), $f(\mathfrak{M})$ , using our estimated primary mass. $\mathfrak{M}_1$ , and $\mathfrak{M}_2$ is a lower limit of $\mathfrak{M}_2$ and $\mathfrak{M}_2$ our estimated primary mass. $\mathfrak{M}_1$ , and $\mathfrak{M}_2$ our estimated primary mass. $\mathfrak{M}_1$ and $\mathfrak{M}_2$ or $\mathfrak{M}_2$ and $\mathfrak{M}_2$ our estimated primary mass. $\mathfrak{M}_1$ and $\mathfrak{M}_2$	. B601	In 7.7	7.11 02	+23 12	9.1/	07 TD	0.162		Q.02	0c.0	 	4.8
The sector of the prime of the prime of the presence of a normal when you can be preteral type. In column $\mathcal{D}(G)$ may $\mathcal{D}(G)$ is a lower that on the mass of the secondary star, stature yielded no convincing evidence (m.s., r. $\mathcal{D}(G)$ , doubling of lines) for the presence of a normal which is obtained from the mass function, $\mathcal{D}(G)$ , using our estimated primary mass, $\mathcal{D}(I)$ , and ondary star. As a result of our survey of the literature, we have adopted different spectral using $\mathfrak{sin} t = 1$ (orbit seen effector). The remaining notation and entries are those of Batten. The remaining notation and entries are those of Batten. Since references to the literature is primary is double with mass ratio 11.2/10.6.	* The entries	in this table include a	ull single-line, noi	n-eclipsing binar	ies listed in Batte	n's number. The	column M1/M6	) is our estim	late of the ma	tss of the pri	mary star, b	ased on its
but your year the many years from the given by Batten. Since references to the literature $\uparrow$ Primary is double with mass ratio 11.2/10.6.	rature yielded	no convincing evidence a result of our survey	e (e.g., doubling v of the literature	of lines) for the	presence of a norn	nal spectral type. nal which is obtained	ined from the ma	s function, $f($	(M), using ou	r estimated p	or the seco	, Muary star,
	bes for some of t	the primary stars from	those given by B	atten. Since refer	ences to the literati	ure using sur t =	r is double with m	e-on). The fell	/10.6.	און כענווכ	ה מוב וווטאב ט	ו המווכחי

itar	 <b>G</b> 1900	Ô1900	Magnitude	Spectral Type	Period (days)	Q	$K_1$ (km sec <sup>-1</sup> )	$f(\mathfrak{M})$	<u></u>	∭t₂ min ∭⊙
ы	20h14m8	$+34^{\circ}40'$	5 16	F5 Ib	2440.0	.506	9.57	0 142	10	2.9
<u> </u>	 20 19 1	-41 07	6.15	K3 III	117 776	.240	22.62	0 130	4.3	1.7
94495	 20 20.8	+21 10	2 00	B7	4.9052	133	82.2	0.275	6.0	2.8
	 20 27.9	+62 39	4.21	A5m, F5 IV	840.6	.03	13.85	0.232	2.0	1.4
-	 20 31.8	+25 32	6.22	A4 III	11.088	.2843	58.7	0.205	2.3	1.4
98784	 20 47 6	+3736	6.97	B3	3.30353	.018	63.81	0.082	10	2.3
99579	 20 53 1	+44 33	5.96	05-6e	48.608	.0988	42.22	0.374	25	7.3
03025	 21 14.6	+58 10	6.42	B2 IIIe	225 44	.226	21.9	0.3956	14.	5.3
04188	 21 21.8	+1858	6.03	A3m	21.724	0	41.45	0 1607	2.8	1.4
09961	 22 02.0	+47 45	6.27	B2 V	2.1721	0	127 7	0.47	12.	5.2
, A	 23 04.7	+7451	4.42	G2 III	556.2	0.281	23 02	0.624	3 0	2.7

TABLE 1-Continued

§ Primary is double with mass function 0.0353.

TABLE 2

SINGLE-LINE BINARIES OF CLASS III (𝔅 𝔅 𝔅 𝔅 𝔅 𝔅 𝔅 𝔅 𝔅 𝔅 𝔅 𝔅) (𝔅 𝔅 𝔅 𝔅)

<u>∭³</u> n	3 7 15., 10., or 6.0	3.3	22.	2.4	6.3	4.4	6.8	14.	2.4
$\mathfrak{M}_1$ $\mathfrak{M}_{\odot}$	$1.8 \\ 12., 5 \\ 0, 1.0 \\ 0r 1.0$	1.9	10.	2.2	1.8	4.0	4.0	10.	2.0
$f(\mathfrak{M})$	$1.70 \\ 4.41$	1.318	10.4	0 635	3.80	1.188	2.72	4.94	0.711
$\frac{K_1}{(\text{km sec}^{-1})}$	15 1 51.4	18.1	31.5	28.6	27 1	17.92	104.5	130	11.31
અ	0.241 .28	46	.31	.549	.353	.264	.35	0	0.544
Period (days)	5200. 360.47	3057	3710.	445 74	2238.6	2214.	27.97	21.64	8016.
Spectral Type	F0 V A0 II, Ape	A9 IV	B3n, e	A4 IV	F0 IV	K2 III	A0, Bge, B9eβ	H9NM	A7 V
Magnitude	$7 \begin{array}{c} 4.51\\60-7\end{array}$ 70	4.39	8.1	4.81	3.52	4.36	77	9 43	4.69
Õ1900	$+15^{\circ}23'$ +43 06	- 5 37	+4053	- 7 16	+22 10	-61 33	+29 10	+3636	- 8 18
<b>C</b> 1909	04 h20m6 04 41.8	04 48.0	05 03 7	05 34.0	07 14.2	18 14.0	19 44.7	20 17.8	21 32.4
Star	71 Tau KS Per	ωEri	HD 33232	49 Ori	δ Gem	ξ Pav	HD 187399	HD 193928	ξ Aqr
No.	1. B127 2. B141	3. B145	4. B155	5. B189	6. B232.	7. B508	8. B576	9. B615	10. B655

1015

1016

1969ApJ...156.1013T

### NOTES TO TABLE 2

General—The entries in this table include all single-line, non-eclipsing binaries listed in Batten's (1968) catalogue, for which (i)  $\mathfrak{M}_{2 \min} > \mathfrak{M}_{1}$ , (ii)  $\mathfrak{M}_{2 \min} \ge 1.4 \mathfrak{M}_{\odot}$ ; and (iii) our own survey of the literature yielded no convincing evidence for the presence of a normal secondary star. See note (\*) to Table 1 for further discussion.

1. 71 Tau = HD 28052.—The broad, poor lines of the primary (only H and Ca II are measureable) may well conceal a second spectrum. The second set of lines reported by Frost, Barrett, and Struve (1929) would seem to imply a period near 100<sup>d</sup>, while Abt (1965) derived a period of  $5200^d$  from the primary spectrum and saw no lines at all that could be attributed to the second star. Abt suggests that in this and other long-period, well-separated binaries, the secondary is itself double or multiple, thus producing a much smaller luminosity than would be produced by a single star of the same mass.

2. K5 Per = HD 30353.—The hydrogen deficiency of the primary suggests to Wallerstein, Greene, and Tomley (1967) that it is a highly evolved, overluminous star with present mass about  $1 \text{ } \mathfrak{M} \odot$  and absolute magnitude about -3. If this is the case, the secondary will have a mass of about 6  $\mathfrak{M} \odot$ , which corresponds to a main-sequence spectral type of B5 with absolute magnitude near -1. Such a secondary might well have remained undetected in the observations that have thus far been carried out.

3.  $\omega$  Eri = HD 31109.—This system has both a rather large separation and an overluminous (evolved) primary. The more massive secondary might therefore be either itself multiple, or single but fainter than the primary.

4. HD 33232.—The observed spectrum is a complicated one, with lines of various elements yielding different values of the orbital elements, especially  $K_1$  (Merrill 1934). The values tabulated are those derived from the hydrogen lines. The lines of Fe II, Si III, and Mg II show larger amplitudes, while the amplitudes obtained from Ca 11 (probably affected by interstellar lines) and He are smaller. The mass function might therefore be seriously in error; and the secondary star might be little, if at all, more massive than the primary. As in other long-period systems, a double or multiple secondary is also a possibility

5. 49 Ori = HD 37507.—Lines of a second star, consistent with the period of  $445^{4}74$  and implying a mass ratio of about 2, were reported on five plates by Frost *et al.* (1929). These lines were not detected by Abt (1965).

6.  $\delta$  Gem = HD 56986.—This system, like  $\omega$  Eri, may include either a multiple secondary or an overluminous primary. The large mass ratio (at least 3) makes it seem unlikely that the primary can be sufficiently luminous to mask a secondary of normal spectrum. 7.  $\xi$  Pav = HD 168339.—This system also has a rather large separation and a primary which may be

overluminous.

8. HD 187399.—This close system is completely inclosed in an expanding cloud giving hydrogen absorption lines at -95 km sec<sup>-1</sup>. (The system velocity is -19 km sec<sup>-1</sup>.) There is also hydrogen emission which gives velocities near that of the system. No good spectral type is available for the primary, and its mass is, therefore, poorly determined. If it is an overluminous, evolved star, the complex spectrum could well conceal any lines due to the secondary. 9. HD 193928.—The primary is a Wolf-Rayet star. At least six systems are known consisting of a

Wolf-Rayet and an O or early B star. In each case the early-type star is the more massive, by a factor of as much as 3-5, without being necessarily the more luminous. The mass ratio of less than 2 for this system is therefore consistent with the secondary star's being sufficiently less luminous than the primary that its spectrum is completely lost among the complicated WN lines. 10.  $\xi$  Aqr = HD 205767.—This long-period system could contain a double or multiple secondary.

40 of Table 1), three contain a primary which has evolved off the main sequence and is probably somewhat overluminous for its mass, thereby concealing the secondary spectrum. The remaining system (no. 6,  $\rho$  Tau) has been reported to show two sets of spectral lines on some plates (Lee 1910), although the velocities found from the second set are quite unreliable. It is unlikely that further optical studies can yield convincing evidence for collapsed or neutron stars among these systems. If any of them should prove to be a strong source of X-rays or gamma rays, however, the case for a collapsed or neutron-star secondary would be greatly strengthened (see § II below).

The systems of *class III*, those in which the unseen secondary is more massive than  $1.4\,\mathrm{M}_{\odot}$  and more massive than the primary, are by far the most interesting, since, other things being equal, the more massive star should be the brighter and should contribute the stronger lines to the combined light of the system. Table 2 lists the class III systems and suggests reasons for the absence of the secondary spectra. Three factors seem to be important. First, in long-period systems of large separation (nos. 1, 3, 4, 6, 7, and 10), the secondary star may itself be double or multiple, rendering it much fainter than expected, since two main-sequence stars of mass  $\mathfrak{M}/2$  give less light than one star of mass  $\mathfrak{M}$ . Second, in many of the systems (nos. 2, 3, 5, 6, 7, and 9), the observed primary star has evolved well off the main sequence and could easily be more luminous than a main-sequence star of larger mass. Third, several of the systems (nos. 2, 4, 8, and 9) have complicated spectra, including emission components, which may help to mask the lines of the secondary star.

For all of these class III systems and for numbers 2, 6, 18, and 40 of class II an effort should be made to detect the secondary, both in high-resolution spectrograms and in color measurements over the entire accessible spectrum. Presence of a normal secondary could be definitely established by detection of its spectral lines or could be strongly suggested by color anomalies. (If the observed light of a system in fact comes from two stars, its intensity distribution might not be normal for the observed spectral type as deduced from the lines.) Failure to detect the secondary star cannot, on the other hand, rule out its normalcy.

### TABLE 3\*

### SINGLE-LINE ECLIPSING BINARIES OF CLASS II

$(\mathfrak{M}_1$	>	$\mathfrak{M}_2$	min	$\geq$	1	4 <b>∭⊙</b> )

No.	Star	No.	Star	No	Star	No	Star
B8	TV Cas	B191 .	32 TU Cam	B380 .	UX UMa	B556	FL Lyr
B15	ZZ Cas	B194	Z Ori	B453	W UMi	B578	V505 Sgr
B22 .	YZ Cas	B199	SV Gem	B504	μ Sgr	B664	EK Cep
B176	EY Ori	B237	AR Mon	B534	β Lyr	B721	AR Cas
B183	$\theta^1$ Ori	B263	UU Cnc	B535 .	HS Her	B727	UU Cas

\* For detailed spectroscopic data on these stars see Batten (1968) The numbers given here for each star are those of Batten.

# II. X-RAYS AND GAMMA RAYS FROM MASS ACCRETION

As pointed out by Zel'dovich and Guseynov (1965), the discovery of X-rays or gamma rays from a single-line binary system, such as those in Tables 1 and 2, would constitute positive evidence for the presence of a collapsed star or neutron star: Matter flowing out from the primary star should accrete onto the collapsed or neutron-star secondary. During this accretion, infalling particles of matter acquire velocities approaching that of light. Collisions of the infalling particles with each other and with the surface of a neutron star should produce gamma rays and X-rays (see Salpeter 1964; Shklovsky 1967; Cameron and Mock 1967).

None of the binary systems of Tables 1 and 2 fall within the error limit of any published X-ray position (tables and references in Friedman, Byram, and Chubb 1967 and in Gorenstein, Giacconi, and Gursky 1967). The positions of the systems in Tables 1 and 2 should be compared with additional X-ray and gamma-ray positions as these become available.

# III. ECLIPSING BINARIES OF CLASSES II AND III

For the purpose of comparison with the systems of Tables 1 and 2, we have also compiled from Batten's catalogue lists of single-line *eclipsing* systems in which the mass of the unobserved star is greater than  $1.4 \text{ M}\odot$ . These are given in Tables 3 and 4. In these systems, the secondary is certainly not either a collapsed star or a neutron star, since the small size of such stars (radius  $\leq 20 \text{ km}$ ) would prevent them from eclipsing any normal star. Their intrinsic faintness, of course, precludes their being the stars eclipsed, even at secondary minima.

The gravitational lens effect is also unimportant for a binary system containing one

;								K,	8	M1	M2 min
No.	Star	<b>a</b> 1900	Ò1900	Magnitude	Spectral Type	Period (days)	o	(km sec <sup>-1</sup> )	f(3116)	Mo	M O
1. B149	e Aur	04 h54m8	$+43^{\circ}40'$	3 0	A8 Ia	9890.	0.172	14.71	3 12	13	13.
2. B501	W Ser	18 04.1	-15 34	9.0-0.0	F5 III†	14.15667	.37	90	0.35	1.4	1.4
3. B534.	$\beta Lyr_{\uparrow}$	18 46.4	+33 15	3.3-4.2	B8pe	12.908	.017	185.0	8.5	50.	41.
4. B631	V367 Cyg	20 44.2	+3855	7 4-8.0	A2 <sup>°</sup>	18.5972	•	93.2	1.56	30	4.4
5. B696.	CQ Cep.	22 32.9	+5623	9 0-9.5	MN6+	1.6410	0 0	295	4.38	10.	13.
* The entries in t (1968) catalogue, for 7 (1968) catalogue, for 7 (iii) $\mathfrak{M}_{2 \text{ min}} \geq 1.4 \mathfrak{M}_{2}$	hıs table ınclude all vhıch (i) only one se ©. For notation see f	spectroscopic, e t of spectral line footnote (*) to T	lipsing binaries s is seen, (ii) M able 1.	listed ın Batten's 2 mın 2 Mu, and	† The line ‡ This sys markable mas	es are largely shell tem 1s actually cla ses.	spectrum, ar iss II by our	id the spectra definitions; bi	l type is very it it is showi	r poorly kno 1 here becau	wn. se of its re-

# SINGLE-LINE ECLIPSING BINARIES OF CLASS III $(\mathfrak{M}_{2\,\text{min}} \ge \mathfrak{M}_1 \text{ and } \mathfrak{M}_{2\,\text{min}} \ge 1.4\mathfrak{M}_{\odot})$

TABLE 4\*

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collapsed star or neutron star; the "lens" is too small and too near the normal star to produce a noticeable effect.<sup>1</sup>

The twenty eclipsing binaries for which  $\mathfrak{M}_{2 \min} < \mathfrak{M}_1$  resemble the class II systems discussed above in that, in most cases, the disparity of masses is sufficiently large that one would not really expect to see the second set of lines. Of the four eclipsing systems for which  $\mathfrak{M}_{2\min} \geq \mathfrak{M}_1$ , one has a large separation and may harbor a multiple secondary, three have non-main-sequence primaries, and all four have complex spectra, including emission lines or a shell spectrum. These eclipsing stars are, therefore, very much like the non-eclipsing class III systems, a fact which certainly does not support the conclusion that the latter include many collapsed or neutron stars.

A second consideration indicates that collapsed stars and neutron stars are, at best, infrequent among the systems of Tables 1 and 2. Single-line binaries with large mass functions are more common among the eclipsing systems in Batten's catalogue than among the non-eclipsing systems. Ten class III systems and forty class II systems were found among about 400 single-line, non-eclipsing binaries, while about seventy eclipsing systems yielded four of class III and twenty of class II.

In spite of possible differences in the selection effects entering into the eclipsing and non-eclipsing samples, it seems highly unlikely that a statistically significant fraction of the class III and III systems harbors collapsed or neutron stars, although a small number of them may do so.

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<sup>1</sup> In quantitative terms, the fractional change in the flux of the normal star due to the gravitational lens effect, when the two stars and the observer are lined up perfectly, is  $\delta \mathfrak{F}/\mathfrak{F} = (1 + 8r_g a/R_1^2)^{1/2} - 1 \ll 1$ , where  $r_g = 2G\mathfrak{M}_2/c^2$  is the gravitational radius of the collapsed or neutron-star secondary,  $R_1$  is the radius of the normal primary, and a is the separation of the two stars.

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