Orbital inclinations of late B-type spectroscopic binaries

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Summary. Information on the orbital inclinations \( j \) of late B-type spectroscopic binaries (SB’s) with periods between 3 and 50 day is obtained from the masses \( M_1 \) of their primary components, derived from \( uvby\beta \) photometry, and the values of \( M_1 \sin^3 j \). The cumulative distribution of \( j \) for a fairly complete sample of double-lined binaries (SB2’s) with Hg–Mn primaries is consistent with that expected for random orientations of the orbital planes. The period-eccentricity relations for Hg–Mn SB’s and normal, sharp-lined SB’s do not differ significantly. Sub-synchronous rotators occur among the components of Hg–Mn SB’s (e.g. HR 266, z Cnc, HR 4072, \( \chi \) Lup and 74 Aqr) and superficially normal SB’s (e.g. 64 Ori, HR 7338 and possibly HR 4892); the sub-synchronous primary of HR 7338 is metal poor. The slow rotation of Hg–Mn stars is probably due to special initial conditions or to a substantial loss of angular momentum during contraction to the main sequence. The orbital periods of three of the SB2’s with non-synchronous Hg–Mn components (HR 266, AR Aur and 74 Aqr) are only about 4 day, and these systems may pose a difficulty for the hypothesis that the abundance anomalies are due to the separation of elements by diffusion in quiescent atmospheres.

1 Introduction

In the study of stellar rotation, a major problem is that the orientations of the spin axes of individual stars are usually unknown. However, for short-period spectroscopic binaries it may be reasonably assumed that the spin axes of the components are roughly perpendicular to the orbital planes. Information on the orbital inclination \( j \) of a spectroscopic binary (SB) may be derived from the mass \( M_1 \) of the primary component and the value, or lower limit, of \( M_1 \sin^3 j \) given by the orbital elements. This method can be readily applied to late B-type binaries, since the masses of B-type stars may be determined from \( uvby\beta \) photometry according to a recent calibration by Balona (1984). To find \( M_1 \), the photometry of the binary has to be corrected for the light from the secondary component. In the case of a double-lined spectroscopic binary (SB2) the mass ratio \( M_1/M_2 \) and a value of \( M_1 \sin^3 j \) may be found; for a single-lined binary (SB1) the absence of a secondary spectrum may be used to set a lower limit for \( M_1 \sin^3 j \). Since \( j \) follows from \( M_1 \sin^3 j \), the method is fairly insensitive to moderate errors in \( M_1 \).
In this paper the inclinations of late B-type SB's with known orbits are derived. As in a previous paper which discussed the rotation of late B-type stars (Guthrie 1982), the term 'late B-type stars' is taken to include stars with MK types A0 or earlier and intrinsic colours \((U-B)_0\) in the range from \(-0.50\) to \(0.00\). This corresponds to the range B6 to A0 in spectral type for luminosity classes III to V. Late B-type stars include the interesting Hg–Mn class of stars and some types of magnetic Ap stars. The occurrence of SB2's is quite common among Hg–Mn stars (Wolff & Preston 1978) but very rare among magnetic Ap stars (Gerbaldi, Floquet & Hauck 1985).

Samples of field stars are taken from the *Bright Star Catalogue* (Hoffleit 1982) and its supplement (Hoffleit, Saladyga & Wlasuk 1983). In Section 2 the orbital inclinations \(i\) of SB's with Hg–Mn components and orbital periods \(P<50\) day are derived. These Hg–Mn stars all have projected rotational velocities \(v \sin i \leq 70 \text{ km s}^{-1}\), \(v\) being the equatorial rotational velocity and \(i\) the inclination of the axis of rotation to the line-of-sight; there are no orbital periods less than 3 day. A corresponding sample of SB's with normal late B-type components is also studied. The detection of SB2's among known Hg–Mn stars is fairly complete, and the cumulative distribution of \(i\) is compared with that expected for random orientations of the orbital planes. In Section 3 the values of \(i\) are used to search for examples of sub-synchronous rotation among normal and Hg–Mn components of SB's.

2 Orbital inclinations of field stars

Hg–Mn stars, which lie near the main sequence and cover the same range of effective temperature \(T_{\text{eff}}\) as normal late B-type stars, are characterized by slow rotation \((v \sin i \approx 90 \text{ km s}^{-1})\) and various abundance anomalies (Wolff & Preston 1978, hereafter WP; Guthrie 1981, 1984). The less prominent anomalies might escape detection in broad-lined stars, but excesses of Mn are easily detected in the spectral region 3440–3500 Å where strong Mn II lines occur. A spectroscopic survey of 194 late B-type stars in this region showed a real decline in the frequency of Mn stars with increasing \(v \sin i\) and did not reveal any Hg–Mn stars with \(v \sin i > 75 \text{ km s}^{-1}\) (Wolff & Wolff 1974). Thus there can be few, if any, broad-lined Hg–Mn stars. The overall incidence of binaries among Hg–Mn stars is similar to that for normal late B-type stars, but SB2's seem to be more common among Hg–Mn stars in spite of a conspicuous lack of periods less than 3 day (Aikman 1976; WP). More than 10 radial velocities have been obtained for most of the Hg–Mn stars in the *Bright Star Catalogue* (BSC). Since the spectral lines in these stars are quite sharp, the detection of short-period SB's should be fairly complete.

Table 1 lists all the known Hg–Mn SB's in the BSC and its supplement with orbital periods \(P<50\) day. Values of \(M_1 \sin^3 i\) were obtained from the *Seventh Catalogue of the Orbital Elements of Spectroscopic Binary Systems* (Batten, Fletcher & Mann 1978) and later papers for the SB2's. For the SB1's it was assumed, following Kitamura (1980), that the absence of secondary spectra implies mass ratios \(M_1/M_2>1.5\). This seems reasonable, since a mass ratio of 1.5 would correspond to a luminosity ratio of about 5 (Smith 1983). The lower limit \(M_1/M_2>1.5\) was used in conjunction with the mass functions, \(f(M)=M_2^2 \sin^3 i/(M_1+M_2)^2\), to derive lower limits for \(M_1 \sin^3 i\). The orbital data for each SB were checked for consistency with other published radial velocities (Abt & Biggs 1972 and subsequent literature), and new preliminary elements were obtained in a few cases. No orbits are available for the short-period SB2's HD 144844 and HD 22207. References for the orbital data are given in the table, but further notes are necessary for some systems.

(i) \textit{HR 266}. This quadruple system contains a short-period SB2 (B9V Hg–Mn+ A1V). The orbital elements derived by Fekel (1979) from observations during 1975 and 1976 were adopted.

(ii) \textit{HR 1402}. WP calculated orbital elements for \(P=20.43\) day but noted that other periods
Table 1. Orbital inclinations of Hg–Mn SB’s.

<table>
<thead>
<tr>
<th>HD</th>
<th>Name</th>
<th>P</th>
<th>e</th>
<th>M2/M1</th>
<th>M1 sin^3 3</th>
<th>T_eff</th>
<th>log L1/M1</th>
<th>j</th>
<th>References</th>
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<td></td>
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<td>0.03</td>
<td>1.69</td>
<td>2.00</td>
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<td>3.75</td>
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<td>4382</td>
<td>23 Cas</td>
<td>33.75</td>
<td>0.41</td>
<td>&gt;1.5</td>
<td>&gt;0.108</td>
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<td>3.05</td>
<td>55: 2</td>
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<tr>
<td>11291</td>
<td>2 Per</td>
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<td>0.02</td>
<td>&gt;1.5</td>
<td>&gt;0.102</td>
<td>11800</td>
<td>2.228</td>
<td>3.44</td>
<td>&gt;18: 1</td>
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<td>0.06</td>
<td>&gt;1.5</td>
<td>&gt;0.00382</td>
<td>11900</td>
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<td>&gt;6: 1</td>
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<td>0.01</td>
<td>1.02</td>
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<td>3.58</td>
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<td>4.51</td>
<td>&gt;23: 3,4,5</td>
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<td>32964</td>
<td>66 Eri</td>
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<td>0.10</td>
<td>1.03</td>
<td>2.45</td>
<td>11000</td>
<td>1.788</td>
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<td>0.50</td>
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<td>2.212</td>
<td>3.52</td>
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<td>34364</td>
<td>AR Aur</td>
<td>4.13</td>
<td>0.01</td>
<td>1.08</td>
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<td>11200</td>
<td>2.020</td>
<td>3.00</td>
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<tr>
<td>78316</td>
<td>β Cnc</td>
<td>6.39</td>
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<td>1.67</td>
<td>0.75</td>
<td>10800</td>
<td>1.908</td>
<td>2.78</td>
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<td>Χ Lup</td>
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<td>0.00</td>
<td>1.42</td>
<td>2.32</td>
<td>10900</td>
<td>1.860</td>
<td>2.72</td>
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<td>143807</td>
<td>ι CrB</td>
<td>35.47</td>
<td>0.56</td>
<td>1.5</td>
<td>0.00025</td>
<td>11300</td>
<td>1.972</td>
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<td>&gt;0.769</td>
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<td>1.972</td>
<td>2.92</td>
<td>&gt;40: 8</td>
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<td>1.72</td>
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<td>13100</td>
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<td>173524</td>
<td>46 Dra</td>
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<td>216494</td>
<td>74 Aqr</td>
<td>3.43</td>
<td>0.05</td>
<td>1.21</td>
<td>1.81</td>
<td>12300</td>
<td>2.160</td>
<td>3.37</td>
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</tbody>
</table>

References:
1 Seventh Catalogue
2 Pekel (1979)  
3 WP  
4 Hube (1970)  
5 This paper

near 20 day, particularly 19.83 day, are possible. A period of 19.84 day is fairly consistent with
three radial velocities measured by Hube (1970) as well as the WP data for this SB1. Preliminary
orbital elements are P = 19.84 day, V0 = +16 km s−1, K1 = 25 km s−1, e = 0.25, ω = 240°.

(iii) HR 1690. WP measured radial velocities for this SB2. Several periods around 25 day are
possible. For P = 25.01 day, preliminary elements are V0 = +22 km s−1, K1 = 74 km s−1, K2 ≈ 79 km s−1, e = 0.50, ω = 90°.

(iv) HR 6620. The orbital elements were taken from the Seventh Catalogue except that the
somewhat larger value K1 = 59.7 km s−1 found by Aikman (1976) was adopted. WP obtained
M1/M2 = 1.72.

(v) HR 7245. Radial velocities measured by Hube (1970) and WP yield preliminary elements
P = 6.9035 day, V0 = −13.5 km s−1, K1 = 12 km s−1, e = 0.

The detection of SB’s among normal late B-type stars is much less complete than for Hg–Mn
stars. Wolff (1978) studied a sample of 83 normal stars in the BSC, but this sample was strongly
biased towards stars with low values of $v \sin i$. Detection of SB's among stars with $v \sin i > 150$ km s$^{-1}$ is difficult and broad-lined SB2's generally escape recognition. The projected rotational velocities of the Hg–Mn primaries of the SB's in Table 1 are all $\leq 70$ km s$^{-1}$, the mean being 18 km s$^{-1}$ (cf. Guthrie 1981). The BSC and its supplement were therefore searched for normal late B-type field stars with $v \sin i \leq 70$ km s$^{-1}$ (Uesugi & Fukuda 1982), and radial velocity data for these stars were gathered from the literature. The SB's known to have periods between 3 and 50 day are listed in Table 2 with references for the orbital data. The mean projected rotational velocity for the primaries is 30 km s$^{-1}$. The restriction $v \sin i \leq 70$ km s$^{-1}$ does, of course, bias the sample towards low inclinations.

The masses $M_1$ of the primaries of the SB's in Tables 1 and 2 were obtained in most cases from $uvby\beta$ photometry (Philip, Miller & Relyea 1976; Hauck & Mermilliod 1980). The effective temperatures $T_{\text{eff}}$ of the primaries were derived from the dereddened indices $c_0$ and $m_0$ using the $c_0$-$m_0$ diagram given by Relyea & Kurucz (1978) for line-blanketed models of solar composition. The derived values of $T_{\text{eff}}$ depend mainly on the values of $c_0$ which were corrected for the light from the secondaries. The corrections to $c_0$ were made using light ratios $L_1/L_2$ given in the literature or derived from the mass ratios $M_1/M_2$ according to the mass–luminosity relationship

$$\log (L/L_{\odot}) = 3.99 \log (M/M_{\odot})$$

(1)

(Smith 1983). These corrections are approximate but amount to only a few hundredths of a magnitude. Corresponding corrections to $\beta$ were also made. No corrections were applied for SB1's, as the corrections are expected to be small and the light ratios are unknown. Absolute visual magnitudes $M_V$ of the primaries were derived from the resulting values of $c_0$ and $\beta$ using the relation

$$M_V = 3.499 + 7.203 \log_{10} (\beta - 2.515) - 2.319 [g] + 2.938 [g]^3,$$

(2)

where

$$[g] = \log_{10} (\beta - 2.515) - 1.60 \log_{10} (c_0 + 0.322)$$

(3)

Table 2. Orbital inclinations of normal late B-type SB's with $v \sin i \leq 70$ km s$^{-1}$ and period $P$ between 3 and 50 day.

<table>
<thead>
<tr>
<th>HD</th>
<th>Name</th>
<th>P (days)</th>
<th>$e$</th>
<th>$M_1/M_2$</th>
<th>$M_1 \sin^3 j$</th>
<th>$T_{\text{eff}}$ (K)</th>
<th>$\log L_1 (L_{\odot})$</th>
<th>$M_1 (M_{\odot})$</th>
<th>$j$ (°)</th>
<th>References</th>
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<td>2.76</td>
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<td>2,3</td>
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<td>2.49</td>
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References:
1. Seventh Catalogue
2. Wolff (1978)
3. This paper
4. Peckel (1979)
5. Hube (1978)
6. Hube & Wolff (1979)
(Balona & Shobbrook 1984), and bolometric magnitudes $M_{\text{bol}}$ were deduced from the values of $M_T$ using the bolometric corrections given by Buser & Kurucz (1978). The luminosities $L_1$ of the primaries in solar units were then found from the values of $M_{\text{bol}}$, taking the solar bolometric magnitude as +4.64 (Landolt-Börnstein 1982). Finally, the masses $M_1$ of the primaries in solar units were obtained from the calibration

$$\log_{10} M = -1.7110 + 0.4225 \log_{10} T_{\text{eff}} + 0.2365 \log_{10} L$$

(Balona 1984). In a few cases photometry was not available, and values of $c_0$, $m_0$ and $\beta$ corresponding to the MK types of the primaries were used (B8V for HD 2019, B9V for HR 266 and(514,210),(984,223)

Batten (1973) discussed possible sources of systematic error in the determination of $M_1 \sin^3 j$ and $M_2 \sin^3 j$ from radial velocity data. The most serious errors arise for SB2's from incomplete resolution of the primary and secondary spectra and distortion of the radial velocity curves by the reflection effect; these would generally lead to underestimates of $M_1 \sin^3 j$ and corresponding underestimates of $j$. For SB2's with $P<50$ day and components with $v \sin i \approx 70$ km s$^{-1}$, the primary and secondary spectra are usually well resolved near the nodes when the difference in radial velocity is greatest. With regard to the reflection effect, corrections to the total mass of the system would be of the order of 0.1 $M_1$ for systems with similar components where the ratio of the radii $R$ of the components to their separation $s$ is between $\sim 0.1$ and $\sim 0.2$ (Batten 1957). However, larger corrections may be required if the radial velocities are determined from lines which are very temperature sensitive (Ovenden 1963). For an SB2 with $P=3$ day and B9V components, $R/s = 0.17$ and the small difference in $T_{\text{eff}}$ between the illuminated and averted hemispheres of each component

$$\Delta T_{\text{eff}} \sim T_{\text{eff}}(R/s)^2/16 = 20 \text{ K}$$

(cf. Guthrie & Napier 1980) would not affect the derivation of $M_1$ from $uvby\beta$ photometry. As the present discussion concerns only SB's with $P>3$ day, no attempt has been made to apply corrections for the reflection effect.

The procedure for deriving values of $M_1$ from $uvby\beta$ photometry should be valid for Hg–Mn stars as well as for normal late B-type stars, since the abundance anomalies in Hg–Mn stars are believed to be confined to their outer layers. The $c_0$ vs $m_0$ diagram used to derive $T_{\text{eff}}$ is based on line-blanketed models of solar composition (Relyea & Kurucz 1978), and a refinement would be to correct the values of $T_{\text{eff}}$ to take account of the more severe ultraviolet line blanketing resulting from the somewhat higher metal abundances in Hg–Mn stars (Guthrie 1984). The deficiencies of helium in the atmospheres of some Hg–Mn stars are not sufficient to invalidate the use of $\beta$ as a luminosity indicator (WP; Heacox 1979). It is worth noting that for AR Aur, an eclipsing Hg–Mn SB2, the value of $M_1 \sin^3 j = 2.48 M_\odot$ obtained from radial velocity data and the value $j = 88^\circ 4$ derived from the light curve (Johansen 1970) imply a value $M_1 = 2.48 M_\odot$, in close agreement with the value $M_1 = 2.51 M_\odot$ derived from $uvby\beta$ photometry.

WP noted that the distribution of $j$ for Hg–Mn SB2's is indistinguishable from that for random orbital inclinations. However, Kitamura (1980), who obtained values and possible ranges of $j$ for 14 Hg–Mn SB's with $P<13$ day (nine SB2's and five SB1's), found a preference for low inclinations which was interpreted as being due to a concentration of the abundance anomalies towards the polar regions of the Hg–Mn components. The masses $M_1$ derived here from $uvby\beta$ photometry are probably more reliable than those obtained by Kitamura from spectral types. Nevertheless, since $j$ is determined from $\sin^3 j$, the values of $j$ for the nine SB2's in common are very similar. The present study adds six SB2's (HR 266, HR 1690, HR 3361, $\chi$ Lup, $\iota$ CrB and HR 6620) and corrects the value of $M_1 \sin^3 j$ for HD 2019 from 1.07 to 2.00 $M_\odot$. Five of the additional SB2's have high inclinations.

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For a sample of binaries orientated at random, the probability of occurrence of an orbital inclination between \(j\) and \(j + dj\) is proportional to \(\sin j\,dj\). Thus, if the total number of SB's is \(N\), the number with \(j < x\) is

\[
N_x = N \int_0^x \sin j\,dj = N(1 - \cos x).
\]  

The cumulative distribution of orbital inclinations for the 15 Hg–Mn SB2's in Table 1 was normalized and compared with the function \(1 - \cos x\) (see Fig. 1). The maximum absolute difference \(D_N\) between \(N_x/N\) for the Hg–Mn SB2's and \(1 - \cos x\) is only 0.174. According to the Kolmogorov–Smirnov test (e.g. Neave 1981), \(D_{15} \geq 0.304\) for a distinction at a significance level of 90 per cent. Thus there is no apparent preference for low inclinations among the Hg–Mn SB2's. Observational discrimination against low inclinations will be slight for Hg–Mn SB2’s, since the orbital velocities of the components of short-period SB2’s are large and the spectral lines of Hg–Mn stars are sharp especially for stars viewed at low inclinations to their spin axes. Recognition of SB2's among Hg–Mn stars is therefore easy even at fairly low inclinations. There is no dependence of \(M_1/M_2\) on \(j\) for the 15 Hg–Mn SB2’s. Thus the existing data for Hg–Mn SB2’s are consistent with their orbital planes being orientated at random with respect to the lines-of-sight and provide little or no support for Kitamura's suggestion that the abundance anomalies are concentrated towards the polar regions of the Hg–Mn components.

![Figure 1](https://example.com/image1.png)

**Figure 1.** The normalized, cumulative distribution of orbital inclinations for the 15 Hg–Mn SB2's is compared with that expected for a large number of SB's orientated at random.

3 Examples of subsynchronous rotation

The components of an SB with \(P < 50\) day are so close that it is almost certain that they were formed in the same process rather than from independent condensations in the interstellar medium. So it is quite plausible to suppose that the spin axes of the components are roughly aligned perpendicular to the orbital plane. This supposition is supported by the fact that for SB2's with mass ratios near unity the projected rotational velocities \(v_1 \sin i\) and \(v_2 \sin i\) of the primary and secondary components are similar. Examples among the SB2's in Tables 1 and 2 are \(\eta^5\) Eri, 41 Eri, AR Aur and 46 Dra (cf. Tables 3 and 4). Assuming then that \(i = j\), the equatorial rotational velocities \(v_1\) of the primaries of the SB2's may be derived from the values of \(v_1 \sin i\) (Table 3). The value of \(v_1 \sin i\) for HR 266 was estimated from the portion of a Reticon spectrogram reproduced by Fekel (1979), and microdensitometer tracings of high-resolution photographic spectra

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Table 3. Comparison of actual, synchronous and pseudosynchronous rotational velocities \(v_1, (v_1)_{\text{syn}}\) and \((v_1)_{\text{ps}}\) in km s\(^{-1}\) for the primaries of SB2's.

<table>
<thead>
<tr>
<th>HD</th>
<th>Name</th>
<th>Type</th>
<th>(v_1 \sin i)</th>
<th>(i)</th>
<th>(v_1) (\sim)</th>
<th>(P) (\text{(days)})</th>
<th>(R_1) (\times 10^6) (\text{km})</th>
<th>((v_1)_{\text{syn}})</th>
<th>((v_1)_{\text{ps}})</th>
<th>References for (v_1 \sin i)</th>
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<td>(\sim 49)</td>
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<td>50:</td>
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<td>1</td>
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<td>HR 266</td>
<td>Mn</td>
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<td>55:</td>
<td>(\sim 12)</td>
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<td>1.86</td>
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<td>97:</td>
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<td>2.02</td>
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<td>(\xi)</td>
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<td>1.96</td>
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<td>Hg</td>
<td>(\xi)</td>
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<td>10</td>
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<td>1.85</td>
<td>39</td>
<td>43</td>
<td>6, 13</td>
</tr>
</tbody>
</table>

References:
2. Pekel (1979)  
3. This paper  
5. White et al. (1976)  
6. WP  
7. Stickland et al. (1984)

(2.4 Å mm\(^{-1}\)) of 46 Dra and HR 7338 were kindly made available to the author by Professor C. R. Cowley.

The resulting values of \(v_1\) were compared with the synchronous rotational velocities \((v_1)_{\text{syn}}\) obtained by making the rotational periods of the primaries equal to the orbital periods \(P\). Thus

\[
(v_1)_{\text{syn}} = 2\pi R_1 / P, \tag{7}
\]

where \(R_1\) is the radius of the primary. The radii \(R_1\) were obtained from the relation

\[
L_1 = 4\pi R_1^2 \sigma T_{\text{eff}}^4, \tag{8}
\]

where \(\sigma = 5.67 \times 10^{-5}\) erg cm\(^{-2}\) deg\(^{-4}\) s\(^{-1}\) (the Stefan-Boltzmann constant). Allowing for possible errors in the values of \(v_1\) and \((v_1)_{\text{syn}}\), there are several cases in Table 3 where the value of \(v_1\) is

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Table 4. Comparison of actual, synchronous and pseudosynchronous rotational velocities \((v_2, v_2, v_2)_{syn}\) and \((v_2)_{ps}\) in \(\text{km} \cdot \text{s}^{-1}\) for the secondaries of SB2's.

<table>
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<tr>
<th>HD</th>
<th>Name</th>
<th>(v_2 \sin i)</th>
<th>(v_2)</th>
<th>(P)</th>
<th>(R_2)</th>
<th>(v_2)_{syn}</th>
<th>(v_2)_{ps}</th>
<th>(A_1/A_2)</th>
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<td>~35</td>
<td>6.36</td>
<td>1.33</td>
<td>15</td>
<td>20</td>
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</table>

significantly lower than \((v_1)_{syn}\) (the Hg–Mn primaries of HR 266, HR 4072, \(\chi\) Lup and 74 Aqr and the A0III primary of HR 7338). Another possible case is the B9V primary of HR 4892. Among the SB1's, the upper limit of \(v_1\) for the Hg–Mn star \(\chi\) Cnc is 8 \(\text{km} \cdot \text{s}^{-1}\), which is much less than \((v_1)_{syn}=29 \text{ km} \cdot \text{s}^{-1}\).

For some of the SB2's, the projected rotational velocities \(v_2 \sin i\) of the secondary components are also known (Table 4) from the same references as given in Table 3. Since the radii \(R_2\) of the secondaries cannot be reliably derived from \(uvby\beta\) photometry, approximate values of \(R_2\) were obtained from \(R_1\) according to the mass–radius relation

\[
\log (R_1/R_2)=0.5561 \log (M_1/M_2)
\]

for main-sequence stars (Giménez & Zambrano 1985). The values \(R_1=1.41 \times 10^6 \text{ km}\) and \(R_2=1.35 \times 10^6 \text{ km}\) given in Tables 3 and 4 for AR Aur, the eclipsing Hg–Mn SB2, are in fairly good agreement with the radii of the components, \(1.27 \times 10^6 \text{ km}\), indicated by the light curve (Johansen 1970). The values of \(R_2\) in Table 4 were used to derive the synchronous rotational velocities \((v_2)_{syn}\) for the secondaries. Both the primary and secondary components of HR 266, HR 4072 and \(\chi\) Lup appear to have subsynchronous rotation.

Values of \(v_1\) and \(v_2\) are known for six of the SB2's in Table 4. Assuming that the structures of the components of each SB2 are similar, the ratios \(A_1/A_2\) of the angular momenta of the primaries and secondaries were derived and are given in the last column of the table. These ratios are near unity and therefore indicate a strong tendency towards equipartition of angular momentum. This holds even for the non-synchronous cases (HR 266, \(\rho^5\) Eri and AR Aur). However, the orbital angular momentum of each SB2 is much greater than the combined rotational angular momentum of its components.

Only seven of the 22 Hg–Mn SB2's have no observed secondary spectrum. The median value of the mass functions, \(f(M)=M_2^3 \sin^3 i/(M_1+M_2)^2\), for these seven systems (0.012 \(M_\odot\)) is much lower than that for the 15 SB2's (0.196 \(M_\odot\)). It is therefore unlikely that they are unrecognized SB2's with broad-lined secondary components.

Some of the normal and Hg–Mn SB2's have quite eccentric orbits. Tidal forces are strongly dependent on distance, and the time-scale for synchronization is considerably less than that for orbital circularization for systems where the orbital angular momentum is dominant. Thus the rotation of the components of an eccentric SB would tend to become pseudosynchronized with
the orbital angular velocity at periastron (Hut 1981). This tendency towards pseudosynchronization has been confirmed by observations of eccentric eclipsing binaries (Giménez & Andersen 1983). Pseudosynchronous rotational velocities \(v_{ps} \) and \(v_{2ps} \) were calculated from the relation

\[
v_{ps} = \frac{v_{syn}(1 + e)^{1/2}}{(1 - e)^{3/2}}
\]

using the eccentricities \(e \) listed in Tables 1 and 2. In addition to the subsynchronous rotators already mentioned, the rotation of the B7V and B8V components of the triple system 64 Ori may be regarded as subsynchronous with respect to their pseudosynchronous rotation velocities (Tables 3 and 4; Fekel 1979).

The knowledge of \(j \) allows a determination of the semi-major axis \(a = a_1 + a_2 \) of each SB2 from the values of \(a_1 \sin j \) and \(a_2 \sin j \). The fractional radii \(r = R_1/a \) of some of the subsynchronous primaries turn out to be quite large (0.14 for HR 266, 0.16 for HR 4892, 0.08 for HR 7338, and 0.15 for 74 Aqr), whereas Giuricin, Mardirossian & Mezzetti (1984) found that a strong tendency towards synchronization, or pseudosynchronization, prevails for early-type components of SB's with fractional radii \(r \) down to about 0.05. The discovery of subsynchronous rotators in Hg–Mn and superficially normal systems is also notable in view of the general absence of subsynchronous rotators among normal B- and A-type components of eclipsing binaries (Levato 1974).

It is very unlikely that the slow rotation of Hg–Mn stars has resulted from tidal or magnetic braking during their main-sequence lifetimes. Some Hg–Mn stars are single, and tidal braking in SB's would not lead to subsynchronous rotation. The surface longitudinal magnetic fields of Hg–Mn stars are \(\lesssim 300 \) G; disordered but locally strong fields are unlikely to be present, since some Hg–Mn stars have extremely sharp lines with no evidence of Zeeman broadening (Conti 1970; Borra & Landstreet 1973, 1980). Magnetic braking on the main sequence is probably not significant even for Ap stars with surface fields of \(10^3 \)–\(10^4 \) G (North 1985; Borra et al. 1985). The slow rotation of Hg–Mn stars has therefore to be attributed to special initial conditions or to a substantial loss of angular momentum during contraction to the main sequence. Young clusters and associations would then be expected to contain some Hg–Mn stars if the time-scale for the production of the abundance anomalies is short. Several Hg–Mn stars have been found in the Scorpius–Centaurus association (Klochkova, Kopylov & Kumaigorodskaya 1981) and HR 1690 (Table 1) is probably a member of the Orion association (Warren & Hesser 1977). Straizys et al. (1982) reported the discovery of a heavily reddened Hg–Mn star HD 29647, close to the Taurus molecular cloud, a region of star formation. However, there are several reasons, for example the lack of a reflection nebula, for believing that this star lies behind, rather than within, the cloud (Crutcher 1985).

Subsynchronous rotators also occur in systems with no Hg–Mn anomalies (e.g. 64 Ori, HR 7338 and possibly HR 4892). No abundance anomalies have been reported for 64 Ori and HR 4892, but a detailed abundance analysis of the primary of HR 7338 by Sadakane (1981) revealed deficiencies of Al, Si, Sc, Ti and Fe. Wolff (1978) obtained nine additional radial velocities of the primary of HR 7338, and all the available data are consistent with an orbital period \(P = 10.3938 \) day. The secondary spectrum is difficult to measure, but its presence was confirmed by Cowley et al. (1982) on a high-resolution spectrum. The value \(M_1/M_2 = 1.39 \) quoted in Table 2 was based on four low-resolution spectra and should possibly be increased to about 1.7 to take account of all the reported measurements of the secondary spectrum; this would imply a slight increase in the value of \(j \) from 50° to 62°. The eccentricity of the orbit is high (\(e = 0.52 \)), and the rotation of the primary is definitely subsynchronous with respect to \(v_{1ps} \).

It is well known that the orbital eccentricities of SB's tend to increase with period (e.g. Staniuca 1979). Selection effects may influence the observed distribution of \(e \) (Staniuca 1982), but they are likely to be similar for Hg–Mn SB's and normal SB's with \(v \sin i \lesssim 70 \) km s\(^{-1} \). Aikman (1976) compared the period–eccentricity relation for Hg–Mn SB's with that for a sample of
normal late B-type SB's with no restriction on $v\sin i$ and found a marginal tendency for the Hg–Mn SB's to have more nearly circular orbits. The period–eccentricity relations for the 22 Hg–Mn SB's in Table 1 and the 11 normal SB's with $v\sin i \leq 70 \, \text{km s}^{-1}$ in Table 2 do not differ significantly, but the number of normal SB's available for the comparison is small. The Hg–Mn+AlV SB2 in the quadruple system HR 266 is exceptional, having a short period ($P=4.24$ day) and a high eccentricity ($e=0.46$).

The abundance anomalies in the atmospheres of Hg–Mn stars are often attributed to a separation of elements by diffusion under the influence of gravitation and radiation pressure. Such a process requires a quiescent atmosphere and would be inhibited by meridional circulation. All known Hg–Mn stars are slow rotators ($v\sin i \leq 90 \, \text{km s}^{-1}$). Since synchronism is quickly established in short-period SB’s and $v_{\text{syn}}=90 \, \text{km s}^{-1}$ for an SB with $P \approx 2$ day, the absence of Hg–Mn SB's with $P<3$ day is not surprising. However, diffusion would also be restricted by the mutual irradiation of the components in an SB2, especially in the case of non-synchronous rotation (Guthrie & Napier 1980; Tassoul & Tassoul 1982). The mutual irradiation would induce temperature gradients over the respective surfaces of the components and streaming away from the substellar points. The streaming patterns would be stable for synchronous rotation. In the case of non-synchronous rotation the illumination would affect the various parts of the stellar surfaces in turn. The streaming velocities are difficult to estimate, but the restriction on diffusion would clearly be most severe for short-period SB2's. The discovery of non-synchronous Hg–Mn components in three short-period SB2's (HR 266, AR Aur and 74 Aqr) is therefore important for assessing the diffusion hypothesis.

Acknowledgments

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Orbital inclinations of late B-type SB's

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