Mon. Not. R. Astron. Soc. **389,** 869–879 (2008) doi:10.1111/j.1365-2966.2008.13596.x

A catalogue of multiplicity among bright stellar systems

P. P. Eggleton[1] and A. A. Tokovinin[2]

[1] *Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA94551, USA*
[2] *Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile*

Accepted 2008 June 16. Received 2008 May 21

ABSTRACT

We consider the multiplicity of stellar systems with (combined) magnitude brighter than 6.00 in *Hipparcos* magnitudes. We identify 4559 such bright systems (including the Sun), and the frequencies of multiplicities 1, 2, . . . , 7 are found to be 2718, 1437, 285, 86, 20, 11 and 2. We discuss the uncertainties, which are substantial. We also consider the distributions of periods of orbits and suborbits. We note that for even more restricted set of 478 systems with $V_{\mathrm{H}} \leq 4.00$, the proportions of higher multiples up to sextuple are progressively larger (213, 179, 54, 19, 8, 5), suggesting substantial incompleteness in even the reasonably well studied larger sample.

This sample can be seen as relatively thoroughly studied for multiplicity, and reasonably representative of stars more massive than the Sun. But the restriction to $V_{\mathrm{H}} \leq 6$ means that our sample contains hardly any systems where *all* components are low-mass main-sequence stars (K or M).

Data on multiplicity are important as a constraint on (i) the star formation problem, (ii) the problem of the evolution of the Galactic stellar population and (iii) the interaction of dynamics and evolution through the effect of Kozai cycles. We discuss these topics briefly.

Key words: binaries: close – stars: statistics.

1 INTRODUCTION

The statistics of stellar multiplicity, i.e. the number of components, the distribution of periods, mass ratios etc., are poorly known, especially for multiplicities higher than two. Yet it is important in many respects, for instance as a characteristic of the star formation process, and as an initial condition for stellar evolution. Our goal here is to determine the observed multiplicity of a reasonably well defined, well observed and moderately large bright star sample. This is probably the best-studied sample of its size, of stars sufficiently massive to be important for Galactic evolution. The disadvantages, as well as advantages, of using a magnitude-limited sample rather than distance-limited sample are discussed below. In a forthcoming paper, the observed statistics of multiple stars will be compared with a simulated sample, including selection effects.

The bright star catalogue (BSC: Hoffleit & Jaschek 1983) is a fundamental resource when considering the stellar population of the Galaxy, or at any rate the nearer parts of the Galaxy. It lists multiplicities, but these are often visual multiplicities that may include line of sight, or 'optical', coincidences. Although roughly limited to magnitude 6.5, it is not entirely complete to this magnitude, and also includes several fainter stars. The multiple star catalogue (MSC: Tokovinin 1997) carefully identifies many multiple systems, but restricts itself to multiplicity ≥3. The *Hipparcos* catalogue (HIP: Perryman et al. 1997) has useful data such as parallaxes and proper motions that can help to distinguish optical from physical systems. The MSC provides Johnson *V* magnitudes of the brightest 'resolved' companion, rather than combined magnitudes for the whole systems. The MSC is constantly updated, and at the time of writing it contains 348 systems with multiplicity ≥3 and $V \leq 6$.

Before counting bright multiple systems, it is necessary to define both 'system' and 'bright'. At a first glance, one would like to define a system as a collection of stars that are gravitationally bound to each other, but not to neighbouring systems. Unfortunately, because gravity is a long-range force, it is difficult if not impossible to draw a clear boundary. The entire Galaxy can be viewed as a single system. Intermediate between the Galactic scale and the scale of individual stars are Galactic clusters, globular clusters (at least two of which are bright enough in total to qualify) and various collections of stars, such as groups and associations, which might qualify as 'systems'. We discuss this issue in Section 2.

For 'bright', we choose the HIP magnitude scale, as being reasonably homogeneous. But the issue of magnitude is somewhat complicated by the fact that we wish to use the *combined* magnitude of the system. The 348 systems of the MSC referred to above involve Johnson rather than *Hipparcos* magnitudes, and when adjusted for *Hipparcos* magnitudes the number is 330.

Three comparable seventh magnitude components can make a sixth magnitude system. The obvious alternative, that we might use

⋆E-mail: eggleton1@llnl.gov

the magnitude of the brightest component, seems to us to introduce an unnecessary extra uncertainty, since for any observing technique there will be systems that are marginally resolved, and the individual magnitudes will be less certain than the combined one. However, logic then dictates that we combine magnitudes even for systems that *are* well resolved. Some bright systems have components several hundred seconds apart. A part of our purpose is to compare the observed distribution of multiples with a theoretical model, and in the latter it is obviously most rational simply to combine the magnitudes of all the components.

Our main reason for preferring the *Hipparcos* magnitude scale is that it averages the magnitude of variable stars in a logical and systematic way. The larger amplitude variables, such as δ Cep and Mira variables, are often listed in catalogues under a magnitude that is not a systematic average, and which may differ from the average by half a magnitude or more.

Our main aim in this paper (Section 3) is to determine as well as possible the *observed* distribution of multiplicity, along with the distribution of periods, for a reasonably large and yet reasonably well studied and complete sample. The fact that the sample is magnitude-limited rather than distance-limited makes it unrepresentative of the lower end of the mass spectrum, but is we believe compensated by the fact that there is in effect much greater signal-to-noise ratio (S/N). Somewhat by coincidence, this sample is in practice rather well representative of those stars massive enough to have significant evolution in the course of a Hubble time. A distance-limited sample would have to go out to ∼250 pc to include *any* O stars; it would then include over 10^7 stars, the vast majority of which would not be at all well studied as to multiplicity. In addition, a considerable majority would be too low mass to have significant evolution within a Hubble time.

2 MULTIPLICITY

The great majority of multiple systems are 'hierarchical', with say a wide 'binary' containing two closer 'binaries'. A few hierarchies can be as many as four deep, as in ν Sco (HR 6026/7) which is one of the two septuple systems in the bright sample. Since there is usually a factor of $\sim 10^2$–10^3 difference in separation, from one level of hierarchy to the next, such four-deep systems are likely to be rare. This large factor accounts for the stability of hierarchical multiples, although in principle, and if the orbits and suborbits are roughly coplanar, a factor of only 3 or 4 allows long-term stability. However, non-hierarchical systems exist, in small numbers. They can be expected to be young and to break up in a few million years as a result of gravitational interaction, and presumably that is why they are rare.

But there is a substantial grey area where non-hierarchical multiples can overlap with clusters. Perhaps the entire Pleiades cluster should be seen as one non-hierarchical system. We prefer to see it as several independent hierarchical systems, but it is not clear that there is any sensible criterion that would compel us to do this.

Note that we use the word 'system', and even the words 'multiple system', to include the possibility of multiplicity one, i.e. single stars. On the whole, we will avoid the word 'star' because this is often used ambiguously, to mean either a system if the individual components are not readily distinguishable, or a component of a system if they are. In this paper, we count systems, and within systems we count components, so far as we are able. We should add that we do not include planets as components, although we note systems that contain planets. This, of course, introduces another grey area, since it is not clear where stars stop and planets begin.

The prototype of a non-hierarchical system is the Trapezium, θ^1 Ori (HR 1893–6), which consists (somewhat surprisingly) of five bright components arranged roughly on the boundary of an ellipse with axes 23×13 arcsec^2: see the adaptive-optics mosaic of Simon, Close & Beck (1999, their fig. 1). The components are distributed non-uniformly around this ring, with angular separations (as seen from the centre of the ellipse) of about 90°, 30°, 30°, 120° and 90°, starting from the brightest component at the South and proceeding anticlockwise. But perhaps we should add to these five components the two main components of θ^2 Ori (HR 1897), about 50 arcsec apart and about 150 arcsec from the ellipse towards the Southeast. Further, these seven components have close subcomponents (12, according to Preibisch et al. 1999). One component, BM Ori (HR 1894), is in fact in a non-hierarchical quintuple *sub*system: BM Ori itself, which is an eclipsing and spectroscopic binary, and two further components making a roughly equilateral triangle about 1 arcsec on the side, one of which is a very close pair separated by ∼0.1 arcsec.

However, we ought not to ignore several thousand other stars which are heavily concentrated towards the Trapezium, and evidently physically associated at some level. Several are within the elliptical curve (at least in projection), and not just outside it. We choose to consider the Orion Nebula Cluster (ONC) as just two independent bright systems, θ^1 Ori C (HR 1895) and θ^2 Ori A (HR 1897), which are the only two among the seven major components which qualify with $V_{\mathrm{H}} \le 6$. They are both hierarchical systems of multiplicity three, if we ignore their possible relationship to moderately close companions.

We identify 17 non-hierarchical systems in our sample. Several of these may be simply the three or more brightest stars in a cluster; and there are a further few possible binaries that may actually be just the two brightest stars in a rather distant cluster (∼1 kpc). Some hierarchical systems appear as non-hierarchical configurations simply because of projection.

Among the bright star sample are several looser groupings, such as 'OB associations' and 'moving groups'. These appear to be the last stages in the evaporation of stars from dense star-forming regions (SFRs) into the general Galactic field. They are probably not bound, and so we treat the members of these groupings as individual systems, but possibly multiple on a small scale, and if so then usually hierarchical.

3 PROCEDURE

We searched a number of catalogues, of which we have already mentioned three (the BSC, MSC and HIP). The BSC is particularly helpful in view of its copious notes. We also used the eighth spectroscopic-binary catalogue (BFM; Batten, Fletcher & McCarthy 1989) and the ninth (SB9; Pourbaix et al. 2004). These two catalogues are also very helpful in view of their copious notes. We added the Catalogue of the Components of Double and Multiple Stars (CCDM; Dommanget & Nys 2002) of close multiples (many of which, however, are optical rather than physical multiples) and the sixth catalogue (VB6) of visual-binary orbits (Hartkopf et al. 2000). We also incorporated information from the GCVS (Samus et al. 2004) on eclipsers and ellipsoidal variables, and from the CHARA survey of speckle observations (Hartkopf, McAlister & Franz 1989; Hartkopf et al. 2000).

The *Hipparcos* experiment also generated a catalogue of double and multiple star measurements, HDMC. It contains mostly the known visual binaries, but also new systems discovered by *Hipparcos*. HDMC frequently obtained solutions for pairs that gave the same parallax and proper motions for close pairs, thus normally confirming their physical association.

We included two tables of data on astrometric binaries by Makarov & Kaplan (2005, hereafter MK), where they considered systems whose Tycho and *Hipparcos* parallaxes and proper motions showed non-linear behaviour with time, i.e. acceleration, suggesting astrometric binaries. There are 348 systems containing such 'astrometric accelerators' in our catalogue. We also included tables from the Galactic Kinematics catalogue of Famaey et al. (2005, GKC), who considered the space motions of a large number of HIP targets and noted those for which there was evidence of radial-velocity variations of an orbital character. Several have published orbits, but many more are from the private collection of R. F. Griffin. For several systems with composite spectra, consisting typically of a red giant and an A or late B star, we give the spectral types obtained by R. E. M. Griffin (soon to be published) as a result of careful disentangling of the two spectra; these types are often rather different from those normally quoted.

In addition to GKC above, we used several catalogues of radial velocities (Andersen & Nordström 1983; Nordström & Andersen 1983, 1985; Grenier et al. 1999a,b) for B, A/F and G/K/M stars in the southern sky. They used the results of several radial-velocity measurements per star to determine significant variation between observations. Although there were too few observations to establish orbits, they found several significant variables, identified as 'VAR'. They also found several marginal cases, indicated as 'VAR?'. We included the former as binaries (or subbinaries), but left out the latter. We included the catalogues of Duqennoy & Mayor (1991) who considered many multiple systems containing bright solar-type stars; of Harmanec (2001) for binaries including Be stars; of Aerts & Harmanec (2004) for binaries including pulsating stars; of Parsons (2004) for triple systems with cool giants and hot dwarfs; and of Lindroos (1985), who attempted to distinguish between physical and optical multiples among many bright and wide systems.

Another catalogue was a private one maintained by one of us (PPE), with about 3000 entries taken from the literature in the interval 1975–2005; this catalogue concentrated on systems which contained stars evolved beyond (or not yet up to) the main sequence, but also contained many bright systems of main-sequence stars. We do not reference this catalogue directly, but instead refer directly to those papers in it, which supplied data that were different from (and, as we judged, better than) data from the principal catalogues mentioned above.

Following McClure (1983) and Boffin & Jorissen (1988), we assume that *all* Ba stars are binaries, with a white dwarf (WD) component. Many Ba stars have indeed been determined to have spectroscopic orbits, and in a small number a WD has actually been detected in the ultraviolet. It is surprising to us, however, that among the 52 Ba stars in our bright sample only 10 have known orbits. Three of these have known WD components: ξ^1 Cet (HR 649), ζ Cyg (HR 8115) and ζ Cap (HR 8204). However, the case for binarity is not just that some are confirmed binaries, but much more strongly that a physical mechanism exists to explain the Ba anomaly in terms of binarity, specifically with a WD companion, and that the anomaly is very hard to explain otherwise.

The situation is rather different for S stars. Some of these may be evolved Ba stars, and so also with WD companions, whether seen or not. But others could be 'intrinsic' S stars, having produced their own abundance anomalies internally. We find only four S stars in our bright sample (including one with spectrum M4IIIS); two of these have known WD companions. The other two have visual companions, which are however too far away to be likely WD remnants of S process donors. Perhaps, the systems are triple, but since they might instead contain intrinsic S stars we consider them for the present to be merely binary.

For pairs of stars that are fairly close but might be optical rather than physical, we define a propinquity parameter

$$X \equiv \log \rho + 0.3V - 3.95, \tag{1}$$

where ρ is the separation in arcsec and V is the magnitude of the fainter component. We expect $X \lesssim 0$ if the component is sufficiently bright and near that only $\sim$1 such coincidence is likely in 5000 cases. The model is based on the approximation that the number of stars brighter than V is

$$\log n \sim 3.7 + 0.6(V - 6.0), \tag{2}$$

and that they are randomly distributed over the sky. Many pairs satisfy the propinquity test, and most of these are already fairly well established as either having measured visual orbits, or common proper motions. However, a handful is equivocal: they may satisfy the propinquity test by a considerable margin, and yet the proper motions from HIP or HDMC, and even the parallaxes, may be quite widely different. Often, though different, they are not significantly different because the measurement errors happen to be several hundred times larger than is normal; it is not clear why the errors are so much larger in a few cases. We tentatively identify a handful of systems where we suspect that the multiplicity is three rather than two, and that is responsible for (i) discrepant proper motions and (ii) unusually large errors.

On the other hand, faint physical components with $X > 1$ are effectively lost in the stellar background, especially near the Galactic plane. Without further work on proper motions, e.g. Lépine & Bongiorno (2007), the propinquity test alone biases the observed statistics towards bright companions.

We accept that some of the systems with negative X are optical, one (HR 2764) despite having $X \sim -0.7$. The parallaxes in this case are very different, but are roughly in agreement with the parallaxes expected from spectral types. The spectra are K3Ib-II and F0V, and yet the magnitudes differ by only 1.8. The parallaxes differ by a factor of 13, which is no doubt very uncertain since one is 0.001 arcsec; but it seems more reasonable that the luminosities differ by a factor of 100–1000 than merely 5. A further optical pair (HR 6008/9) has X substantially less than zero; two exceptions in $\sim$5000 are acceptable statistically, just.

Parsons (2004) has identified a substantial number of $n \geq 3$ systems among stars whose spectral energy distribution (SED) has been measured over a wide wavelength range (0.13 – 0.9 μ), putting together data from *International Ultraviolet Explorer*, Tycho and ground-based measures. The presence of two (at least) separate sources, one hot and one cool, is much more evident with such a range than in an SED that is limited to the classic UBV range (0.39 – 0.6 μ). It is often possible to determine the two temperatures separately, by fitting the SED to judicious combinations of single-star SEDs, and this also determines the relative luminosities and radii. Since the parallaxes are known from Tycho/*Hipparcos* as well, the absolute luminosities and radii are known, and can be compared to theoretical isochrones. Parsons finds several systems where the hot star is too bright, compared with a theoretical model, by a factor of $\sim$2, and concludes that the hot component is a subbinary of two roughly equal components. Parsons (2004) lists 19 systems which feature in our catalogue. In four of them, the hot component is already known to be a subbinary of short period, either spectroscopically or photometrically; although in one of these four (β Cap, HR 7776), the subbinary is single lined and therefore the unseen subcomponent cannot be contributing significantly to the SED. However, HR 7776 (Table 1) appears to be sextuple, and it is possible that the nearest of the three remaining components, at ∼0.8 arcsec, contributes something.

In estimating the multiplicity for a particular system in the present compilation, we use a different, and weaker, criterion than the MSC for the certainty with which the multiplicity has been determined so far: in legal terms, our criterion is roughly ‘on the balance of probabilities’ rather than ‘beyond reasonable doubt’. Given our present knowledge, we ask what is the most probable multiplicity. Clearly in some marginal cases, the multiplicity with the highest probability may have a probability only slightly over 50 per cent. For inclusion in the MSC, the criterion was normally stronger; that radial-velocity orbits had actually been determined, for example, rather than suspected on the grounds of significant radial-velocity variability.

4 RESULTS

Table 1 illustrates our results. The main body of the table is available electronically in full; and in the printed version here, Table 1 includes only a few examples, with a range of multiplicities. Many systems consist of two or more HR entries; we list them under the largest relevant HR number (Column 1). Table 2 is a table of cross-referenced names (not shown here in full but available electronically as Supporting Information in the online version of this article); we give the HR, HD, HIP and other identifiers for all components that have HR numbers, so multiple systems which include several HR numbers can be easily found. For systems at the end, which have no HR number, we give a ‘pseudo-HR’ number greater than 9200 and prefixed by P. These are identified with genuine names (HD, HIP, . . .) in the same cross-reference table.

Column 2 of Table 1 lists what we consider to be the most reasonable multiplicity. A multiplicity n that is ≥ 3, and *not* followed by a query or colon, is the same as in the MSC (316 cases); a colon indicates that it is in the MSC with a different $n \geq 3$ (13 cases) and a query indicates that it is not in the MSC (75 cases). Most of the last category are systems where we feel that the balance of probability lies with $n \geq 3$ but that the information is not so compelling as to make the multiplicity say 95 per cent certain.

Column 3 contains some reference letters, defined in more detail shortly. Column 4 contains the parallax from *Hipparcos*, except that a *Hipparcos* parallax <0.001, including values like −0.002, is replaced by 0.001 automatically. Column 5 contains our description of the configuration of the system using nested parentheses in roughly the format suggested by Evans (1977). For each individual component, we give a magnitude and a spectral type, where we can find them, and for each pair of components we give either a period or a separation in arcsec, where we can find them. Our reason for preferring this notation here is that, from experience, it can summarize a system sufficiently clearly that one can readily see where each component is in the hierarchy, and yet it only takes one line per system. To convey substantially more information, both about the subcomponents and the suborbits, we would need at least one line for each subsystem, as in the MSC.

Although the one-line summaries exemplified in Table 1 may not look machine readable, they are. A short code along with the data allowed the following Tables 4–6 to be generated automatically. Various subsets, e.g. systems with WDs, or with semidetached subbinaries, can be quickly identified.

The magnitudes come from HIP if available, and the spectral types generally from the BSC or the MSC if available. HIP magnitudes are given to two decimal places (dp) and other magnitudes, mostly Johnson V, to only one. Sometimes combined magnitudes of subsystems are given as well, and always the overall combined magnitude. Sometimes we have to combine Johnson magnitudes with HIP magnitudes to reach a combined magnitude; but the Johnson magnitudes are usually quite faint and so we treat the combination as a HIP magnitude.

The separation is given to 3 dp if it comes from *Hipparcos*, and only 2, 1 or 0 if from another source. The period is in days if it comes from a spectroscopic or eclipsing binary; the reference is to SB9 or GCVS by default, but the letter ‘s’ implies an individual reference listed in the electronic version. The period is in years if it comes from a visual binary; the reference is to VB6 by default. Most systems with multiplicity $n \geq 3$ come from the MSC, by default, but the letter ‘s’ implies an individual reference, and in some cases letters such as AE (see below) explain why we think it is triple, though not with as high probability as would warrant inclusion in the MSC.

Some published visual orbits have periods in excess of 300 yr. We characterize all of these by a separation rather than a period, feeling that an orbit should be seen revolving at least once (and preferably twice) before being considered reliably determined. In fact, several visual orbits with periods substantially less that 300 yr are quite tentative.

The reference letters in column 3 have the following significance. By default, i.e. in the absence of a reference letter, a system with $n \geq 3$ comes from the MSC, and with $n \leq 2$ from SB9, USNO, BSC, GCVS and/or CCDM, supplemented by HIP or HDMC. Systems with orbits from SB9/GCVS or VB6 are distinguished by having the period in days or years, respectively. When a reference letter *is* given it has the following meaning.

(i) A is for an entry that has been identified as a probable astrometric binary by MK; this presumably has a long period, and so if the system is already known to have a short period (from SB9, GCVS, or another source), we assume the system is triple (at least). If this makes it a triple that is *not* in the MSC, we write $n = 3$? rather than $n = 3$. Quite often it is in the MSC, however, because there is convincing additional evidence.

(ii) b is for an entry of two or more stars that are (usually) intrinsically bright, distant and not very close together. They are close enough together that their juxtaposition is unlikely to be chance, yet far enough apart that one can question whether they are in a long-lived orbit. It ends up as largely a subjective matter whether one thinks these should be listed as one system, or two or more systems. In some cases, they may be members of a cluster, and (arguably) not much closer together than cluster stars usually are. We list eight systems that we qualify with b.

(iii) C is for an entry that comes from CHARA.

(iv) E is for an entry identified in the GCVS as having an eclipsing, or eclipse related, light curve. If a system merits both A and E we regard it as a probable triple, since an orbit that gives eclipses will usually be too small to also give an astrometric indication. Most but not all systems flagged E from the GCVS have known periods, coinciding with SB9 periods, but those without periods are presumably rather uncertain.

(v) G is for a system whose parameters are taken from the catalogue of R. E. M. Griffin (to be published). These are mostly G/K giants plus B/A dwarfs; but in a handful of cases, she concludes that the dwarf is itself in a subbinary.

(vi) H is for a system that we identify, through slightly discrepant proper motions, as having an extra, unseen, component making

Table 1. Sample configurations of bright multiple systems.

mHR	n	Reference	Parallax	Configuration
4:	1		0.009	5.71G5III
91:	3	s	0.002	5.55 [5.95(B5IV + ?; 25.42d, $e = 0.12$) + 6.84; 152.7y, $e = 0.10$]
120:	2?	A	0.022	5.75 (F2V + ?; ?)
136:	6		0.021	3.42 {3.68[4.33(B9V + 13.5; 2.4 arcsec) + 4.55(A2V + A7V; 44.66y, $e = 0.74$); 27.060 arcsec] + 5.09(A0V + A0V; 0.1 arcsec); 540 arcsec}
142:	3		0.048	5.32 [5.61(F8V + ?; 2.082d) + 6.90G0V; 6.890y, $e = 0.76$]
152:	2	R	0.005	5.26 (K5III + ?; 576.2d, $e = 0.30$)
165:	3	R A	0.032	3.43 [(K3III + ?; 20158d, $e = 0.34$) + 13.0M2; 28.7 arcsec]
233:	3?	G	0.004	5.47 [(G8IIIa + (B9V + ?; 1.916d); 2091d, $e = 0.53$]
382:	2?	b	0.001	4.95 (5.11F0Ia + 7.08B6Ib; 134.061 arcsec)
439:	2	C	0.002	5.82 (K0Ib + B9V; 0.11 arcsec)
553:	2	s	0.055	2.70 (A5V + G0:; 107.0d, $e = 0.89$)
629:	2?	h	0.012	5.67 (6.07B9V + 6.95A1Vn; 16.690 arcsec)
958:	2	R G s	0.004	5.68 (K0II + A7III; 115.0d)
1556:	2	s	0.006	4.74 (WDA3 + S3.5/1-; ?)
1564:	4	R R s	0.031	5.28 [(5.67F0IV + ?; ?) + 6.59(F4V +?; ?); 12.500 arcsec]
1788:	5?	s E E	0.004	3.29 [3.58((B1V + B2e; 7.990d, $e = 0.01$) + (B: + ?; 0.864d); 9.50y, $e = 0.2$) + 4.89B2V; 1.695 arcsec]
2788:	3	A E s	0.023	5.79 [(F1V + G8IV-V; 1.136d, SD) + ?; 93.89y, $e = 0.50$]
3963:	3?	h R s	0.007	5.91 [6.30(B8V + ?; ?) + 7.24B9III-IV; 21.200 arcsec]
4621:	5:	A A b	0.008	2.32 [2.52(B2IVne + ?; ?) + 4.40(B6IIIe + ?; ?) @ 325°, 267 arcsec + 6.5B9 @ 227°, 220 arcsec]
4908:	2?	L	0.002	5.37 (O9Ib + 11.8K0III; 29.1 arcsec)
5340:	1	s	0.089	0.11K1.5IIIFe-0.5
6046:	2	R A s	0.005	5.77 (5.7K3II + 8.7K0IV-V; 2201d, $e = 0.68$)
7776:	6	P O	0.009	3.14 {3.21[(G8II + 7.2(B8V + ?; 8.68d, $e = 0.36$); 1374d, $e = 0.42$) + 8.3; 0.8 arcsec] + 6.09(6.16A0III+ 9.14A1; 0.68 arcsec); 205.3 arcsec}
9072:	1?	s	0.031	4.12F4IV
P9203:	3?	H b	0.004	5.79 [6.44(B5/6V + ?; ?) + 6.67B8/9V; 129.490 arcsec]
P9207:	1		0.007	5.99M8IIIvar

The full version of the table can be found in the Supporting Information in the online version of this article.

For systems containing more than one HR component, we use the maximal HR number, called ‘mHR’ (Column 1). If there is no genuine HR number in the system, we give a ‘pseudo-HR’ number, ≥9201, prefixed by P. The corresponding HIP and/or HD numbers can then be found in the cross-reference Table 2. One example shown here, P9203, is HIP 32256 and 32269. We identify only seven pseudo-HR systems that qualify for our sample. Column 2 (n) is the estimated most probable multiplicity.

In Column 3, the letters refer to various sources, as described in the text. The absence of a reference letter also implies particular catalogue sources, as also described in the text. Column 4 is the parallax from Hipparcos, but (a) rounded up to 0.001 arcsec if less than this (including zero and negative values) and (b) averaged, if two or more components appear to be part of the same system and yet have somewhat different listed parallaxes (e.g. HR 126/127/136).

A question mark in Column 5 (Configuration) indicates the presence of a component or an orbit that is inferred, but not directly seen, as indicated by the reference.

the system at least triple. There are six such systems; we assign their multiplicities as 3?, indicating that we think that the probability of the extra body is over 50 per cent, though nothing like certain enough for inclusion in the MSC.

(vii) h is for a binary system where we suspect that large but uncertain discrepancies in the HIP values of parallax and/or proper motion may be hinting very weakly at a third body. We assign multiplicity 2?, and we identify 25 such systems.

(viii) L is for a system where we have relied on the discussion by Lindroos (1985) as to whether certain companions, usually rather distant, are optical or physical, and arguably pre-main sequence if physical.

(ix) P is for a system noted by Parsons (2004) as containing a hot component that may be two roughly equal components.

(x) R is for an entry identified as a probable or certain spectroscopic binary by Famaey et al. (2005), Andersen & Nordström (1983), Nordström & Andersen (1983, 1985) or Grenier et al. (1999a,b).

(xi) s is for a specific reference which is given in the electronic version of the table.

Although nested parentheses are a good way of displaying hierarchical character, they do not work for non-hierarchical systems. For these we use the following notation. Suppose that X, Y and Z are a non-hierarchical triple. Then, we write it as

$$X + Y@\theta, \rho + Z@\theta', \rho'$$

with position angle θ in degrees and separation ρ in arcsec. Both are measured from component X. An example in the printed Table 1 is HR 4621.

We attach considerable weight to *Hipparcos* observations, but we should note that *Hipparcos* claims that α Boo (HR 5340), at a distance of only 11 pc, is a binary with $\Delta V_{\mathrm{H}} = 3.33$ and separation 0.260 arcsec. Griffin (1998) has shown that this is very difficult to reconcile with the record of radial-velocity measurements, which are many and accurate. It is hardly conceivable that such a companion would not have produced a recognizable radial-velocity curve over the last 50 yr. Nevertheless, the issue may still be open: see Söderhjelm & Mignard (1998) and Verhoelst et al. (2005). We list it as single, believing that the companion is an artefact.

We discuss the small subset of entries listed in Table 1, mainly to aid the reader in seeing why we put forward the multiplicities listed there. We refer to the electronic version of the table as the 'EV'.

HR 4 The absence of reference letters implies that the parallax and magnitude come from HIP, and the spectral type from BSC; and there is no clear, or even tentative, indication of any companion in any of the catalogues consulted, or indeed in any paper we have seen.

HR 91 An absence of reference letters, coupled with the fact that the multiplicity is $n \geq 3$, would mean that the basic source of the data is the MSC; but the magnitudes come from HIP. However, the reference letter 's' means that some data (the shorter orbit) comes from a paper referenced in the EV, and in fact the longer period, taken from VB6, is moderately different from the MSC.

HR 120 This is an 'astrometric accelerator' from MK, which we therefore suppose to be a binary with an unseen companion and unknown (but presumably fairly long period) orbit.

HR 136 This is actually three HR stars (126/127/136), but we label it by the largest HR number. The system is a wide but apparently hierarchical triple of three close binaries. The three HIP parallaxes differ by a surprising 20 per cent, and the three proper motions are

Table 2. Sample from cross-reference table.

Galactic longitude	Galactic latitude	mHR	HR	HD	HiP	GCVS	Bayer	Flam-Steed	BD/CoD /CpD	ADS	CCDM /WDS	IDS/MSC	Cluster
306.78	−54.02	HR136	HR126	HD2884	HP2484		betTuc1		CP-63d50			00270-6331	
306.78	−54.01	HR136	HR127	HD2885	HP2487		betTuc2		CP-63d50		00315-6257	00270-6331	
120.84	0.14	HR130	HR130	HD2905	HP2599	kapCas	kapCas	15Cas	BD+62d102				CasOB14
116.94	−42.36	HR131	HR131	HD2910	HP2568			52Psc	BD+19d79	ADS452			
114.55	−55.61	HR132	HR132	HD2913	CHP2548	NSV15113		51Psc	BD+06d64	ADS449	00324+0657	00272+0624	
306.54	−53.97	HR136	HR136	HD3003	HP2578		betTuc3		CP-63d52			00270-6331	
54.20	−39.26	PHR9207	PHR9207	HD207076	HP107516	EPAqr			BD-02d5631				
206.01	32.32	PHR9209	PHR9209	HD73598	HP42497	NSV4171			BD+20d2150	ADS6915	08399+1933		NGC2632
206.00	32.34	PHR9209	PHR9209	HD73618					BD+20d2152	ADS6915	08399+1933		NGC2632
206.02	32.34	PHR9209	PHR9209	HD73619		NSV4174			BD+20d2153	ADS6915	08399+1933		NGC2632

The full version of this table can be found in the Supporting Information in the online version of this article.

The first two columns are galactic latitude and longitude. The next two columns, mHR and HR, give the system number and the component number, which may differ if a system contains more than one component with an HR number – for example, HR 126/127/136. In a small number of cases at the end, systems and components have no HR number, and so are given a 'pseudo-HR' number, of no significance except to cross-reference Tables 1–3. The remaining columns are standard identifiers, except that Greek letters in Bayer names are rendered by the first three letters (or if necessary only two) of the usual spelling in English.

Table 3. Sample from reference table.

mHR	Reference	
91	ApJ655,473	
553	Obs108,228	
958	JAA11,491	
965	Obs109,180	http://www.eso.org/gen-fac/meetings/ms2005/griffin.pdf
1556	ApJ327,214	

The full version of the table can be found in the Supporting Information in the online version of this article. mHR is the maximal HR number as in Table 1.

Table 4. Multiplicity frequency in four samples.

Sample	Total	$n = 1$	2	3	4	5	6	7	Average
$V_{\mathrm{H}} \leq 6$	4559	2718	1437	285	86	20	11	2	1.53
$V_{\mathrm{H}} \leq 4$	478	213	179	54	19	8	5	0	1.84
North	2141	1233	697	140	52	11	7	1	1.57
South	2417	1484	740	145	34	9	4	1	1.49

The last column is the average multiplicity or ‘companion star fraction (CSF)’, defined as $\sum_n nN_n / \sum_n N_n$. If $N_n \propto a^{-n}$, the average is $a/(a-1)$. The first two samples include the Sun, the last two exclude it.

somewhat different, though not alarmingly so. Probably, the internal motions of the three binaries account for most or all of this. The system is accepted as real by the MSC. Our parallax is the mean of the three.

HR 142 With no reference letter (unlike HR 91), the data are straight from the MSC, except for the magnitude from *Hipparcos*.

HR 152 This is a radial-velocity variable flagged by GKC; in fact it has a known orbit, in SB9 (by default), which we presume is responsible for the variation.

HR 165 This is both a radial-velocity variable from GKC, and an astrometric accelerator from MK. We assume that both of these are accounted for by the spectroscopic orbit which is (by default) in SB9. The separation of the third component, quoted to only 1 dp, comes from the BSC. However, if the separation was quoted to 3 dp, it would be a HIP measurement, where there is normally supporting evidence from common, or nearly common, proper motion. The unseen companion in the spectroscopic orbit might, in principle, be a WD, but the mass function is sufficiently small that an M dwarf cannot be ruled out.

HR 233 This $n \geq 3$ system is not in the MSC, hence ‘3?’. R. E. M. Griffin finds an inner orbit of 1.916 d. ‘G’ is a reference to R. E. M. Griffin (to be published).

HR 382 A pair of intrinsically bright, distant stars, part of the cluster NGC 457. They are the two brightest members by ~2 mag, and some way to one side of the cluster centre as defined by about half-a-dozen stars of magnitude 9–10. Their projected separation is ~0.67 pc, about 2.5 pc from the centre. They seem to be on the rather broad margin between indisputable binaries, and pairs or small groups of stars that clearly have a common origin but may no longer be bound. We note eight such systems, referenced with letter b.

HR 439 The separation comes from CHARA. Since it is small, it may be well changing quite rapidly; we simply list the value quoted at the epoch of measurement.

HR 553 Although the orbit is in SB9, the spectral type of the companion is not; the ‘s’ means that a specific reference is given for this.

HR 629 The ‘h’ implies that this is a system where the difference in HIP proper motions is rather larger than we would expect as a result of the well-known companion at 17 arcsec. However, one of the proper motions is unusually uncertain. We therefore entertain the possibility that a third body is present to disturb one of the two known bodies, but do not feel that the probability is high enough to raise the multiplicity from 2? to 3?.

HR 958 This is a radial-velocity variable from the GKC, but an orbit is known which presumably accounts for this. It is not in the SB9 so the flag ‘s’ implies a specific reference to it (in the EV). The spectral types are referenced to ‘G’ (i.e. R. E. M. Griffin, to be published); they are more precise than the K1IIIep + A6V given in the BSC.

HR 1556 The ‘s’ implies a specific reference (in the EV), to the fact that the companion is known to be a WD.

HR 1564 This visual binary contains two radial-velocity variables, as indicated by the MSC (as well as by the double entry, implied by RR, in the GKC).

HR 1788 This complex system is based on a specific reference (De May et al. 1996), as implied by ‘s’. In addition to the eclipse period of the first subbinary listed, there is a second period (0.864 d) which comes from some other component. It is most probably ellipsoidal variation, and while it might come from the B2V component, the second-last component listed, De May et al. conclude that it is probably from the component we have indicated.

HR 2788 This is a well-known Algol (R CMa), but it is also an astrometric accelerator (MK). The latter can hardly be due to the small orbit of the Algol, and so we could infer a distant third body. In fact such a body is known, and listed. There are other systems where both ‘A’ and ‘E’ make it clear why we suppose them to be triple. There are four such AE triples in our catalogue. SD in the description stands for ‘semidetached’; we note 18 such systems in the entire sample. We flag contact systems with CT, and there are three such systems.

HR 3963 *Hipparcos* gives very different parallaxes (0.007, 0.001 arcsec) and fairly different proper motions; thus, the system appears to be optical. Yet a factor of 7 in distance seems entirely at odds with the fact that the spectral types and magnitudes are fairly consistent with their being at the *same* distance. Also they are *very* close for an optical pair; we would only expect one such pair in a sample 10 times larger. We suggest that the smaller parallax is wrong because of an unseen third body, and that this accounts for the difference in proper motion also.

HR 4621 This is a non-hierarchical triple in the MSC, but two components are astrometric accelerators. Thus, we conclude that it may have $n = 5$; the triple is too wide to account for the acceleration without other bodies.

HR 4908 This apparently improbable juxtaposition of an O supergiant with a faint K giant companion is suggested by Lindroos (1985) to be a physical system in which the secondary is still contracting to the ZAMS. Lindroos suggests several other pre-Main-Sequence companions to young massive stars.

HR 5340 We have already discussed the fact that this star (α Boo) is perceived as binary by HIP, but can hardly be binary in the face of much radial-velocity information to the contrary. The ‘s’ flag indicates that we give specific references.

HR 6046 This is both an astrometric and a radial-velocity variable, but both are presumably accounted for by the known orbit. SB9 gives an approximation to the orbit, but our flag ‘s’ points to a specific reference (in the EV) which we believe is better.

HR 7776 This sextuple is rather complex, with conflicting interpretations. We accept that of the MSC. The flag ‘P’ indicates that Parsons (2004) considered that the system needs an extra hot component.

HR 9072 The flag ‘s’ points to two specific references which flatly contradict each other. One says the system is triple, the other single (or at least not demonstrably multiple). It is probably a γ Dor variable, with intrinsic pulsation capable of masking, or being mistaken for orbital motion.

P9203 This is a pair of non-HR stars (HIP 32256 and 32269) which are rather far apart on the sky and yet which are both sufficiently bright that the propinquity factor ($X = 0.2$) is uncomfortably small for an optical pair. Their parallaxes are the same, but their proper motions differ modestly, to the extent that we invoke an unseen third body to account for the discrepancy. Their luminosities are uncomfortably equal considering the difference in spectral types, but not unreasonably equal. If they are a real pair, their combined magnitude puts them in our catalogue, and since they would then be an $n \geq 3$ system we flag them with ‘$n = 3$?’, i.e. not in the MSC. We assign a ‘pseudo-HR’ number ($\geq$9201), and give the actual ID in the electronic cross-reference table.

P9207 This is a Mira variable whose average magnitude as determined by HIP puts it in our sample. It is not in the HR catalogue, but is HIP 107516 as given in the cross-reference table.

Table 4 gives the numbers of systems observed with multiplicity from one to seven, for four samples. The first two are $V_{\mathrm{H}} \leq 6$ and 4; the last two are the first sample divided into northern and southern hemispheres. Note that the Sun is included as a bright star in the first two samples, but is not included in either the north or the south sample.

Table 5 gives the distribution of orbital periods, in bins of width 1.0 in $\log P$ (yr). For wide systems with only a separation listed, the period is estimated from the angular separation, parallax and Kepler’s law, assuming a mass dependent on spectral type. The distribution is broken up into separate distributions according to the spectral type of the main component; type B is divided into early B (B0 to B3.5) and late B. The distribution of period can be seen to be strongly bimodal at early types, becoming weakly bimodal or unimodal with a very broad maximum, at later types. The minimum where it appears is generally in the bins 0.1–10 yr.

Table 6 gives the fractional multiplicity, broken down by the spectral type of the leading component. We see that O stars (which for our purposes include two Wolf–Rayet systems) appear to be substantially more multiple than later types. However, there seems to be little variation in fractional multiplicity among types B–G.

Table 5. Period distribution in systems and subsystems.

$\log P$ (yr) spectral		−3.0	−2.0	−1.0	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	Total
O	0	5	11	5	0	4	3	6	12	1	0	0	0	47
eB	0	25	41	21	14	21	26	29	33	21	3	0	1	235
lB	0	25	53	24	20	43	62	63	48	16	8	0	0	362
A	0	27	62	25	46	78	78	66	47	24	9	0	0	462
F	0	14	33	24	39	46	61	44	26	14	3	1	0	305
G	1	7	9	20	40	38	49	38	32	23	6	1	0	264
K	0	4	4	12	56	35	35	42	35	26	4	0	0	253
M	1	0	0	3	7	6	4	9	9	3	3	0	0	45
Sum	2	107	213	134	222	271	318	297	242	128	36	2	1	1973

The first column gives the spectral type of the dominant body in the system: eB means early B, i.e. B0 – B3.5, and lB means later B. Wolf–Rayet stars (2) are included under O; S and C stars are included under M. The first column of integers gives the number of systems and subsystems with $\log P$ (yr) ≤ -3.0; the second for $-3.0 < \log P \leq -2.0$, etc. The two shortest periods are a contact binary subsystem of the G dwarf 44 Boo (HR 5618), and a cataclysmic binary subsystem of the M giant CQ Dra (HR 4765). Long periods are estimates from the angular separation, distance and Kepler’s law.

Table 6. Fractional multiplicity by spectral type.

Spectral	1	2	3	4	5	6	7	Average	tot_6	tot_4
O	0.342	0.263	0.184	0.105	0.053	0.053	0.000	2.42	38	7
eB	0.531	0.312	0.115	0.020	0.015	0.002	0.005	1.70	401	84
lB	0.541	0.329	0.093	0.032	0.002	0.003	0.000	1.64	653	63
A	0.540	0.362	0.068	0.018	0.006	0.005	0.000	1.61	928	90
F	0.526	0.379	0.062	0.026	0.007	0.000	0.000	1.61	578	49
G	0.550	0.370	0.056	0.020	0.002	0.002	0.000	1.56	588	60
K	0.709	0.253	0.031	0.008	0.000	0.000	0.000	1.34	1043	99
M	0.821	0.155	0.021	0.003	0.000	0.000	0.000	1.21	330	26

Early B stars (B0–B3.5) are called ‘eB’; later B stars are called ‘lB’. Wolf–Rayet stars are included under O; S and C stars under M. The third last column is the average multiplicity; the last two columns are the total number, in the larger sample ($V_{\mathrm{H}} \leq 6$) and the smaller sample ($V_{\mathrm{H}} \leq 4$), respectively.

It is not surprising that our G/K sample should be little different from our A/F sample, since most of our G/K sample are evolved giants and are essentially the same population as the A/F sample (mostly main sequence); but there is little variation even for eB and lB, where the relation is less close.

5 COMPLETENESS, DETECTION EFFICIENCY AND SELECTION EFFECTS

One might suppose that it would not be difficult to identify the complete list of systems with $V_{\mathrm{H}} \leq 6$, supposing for the moment that we are not yet interested in the individual multiplicities. There are, however, minor issues, which make for an uncertainty of perhaps ±10 in our list of 4559 systems. The main one is deciding whether two or more stars, each fainter than $V_{\mathrm{H}} = 6$, are a real system or not. We believe that there is no answer to this that everyone would accept; and the main reason for this is the long-range character of the gravitational force, something that we cannot vary or work around. Nevertheless, we have tested a number of algorithms in which brightness is added up for all *Hipparcos* targets that are closer together than some limit – either an angular limit, or a linear limit involving parallax. With appropriate choice of limit, we can pick up clusters as spread out as the Hyades, but we have concentrated on smaller limits, in particular 180 arcsec. This produces 130 pairs or higher multiples, in addition to many more that qualify only as single targets in HIP but as multiples in the HDMC catalogue. The great majority of the 130 are well-known 'systems' whose reality has been investigated over decades or centuries, and where there is rather little doubt of the reality or otherwise. But we always come across a few near the margin, wherever and however we might try to define the margin. The smallest angular separation that we accept as optical (among pairs of nearly equal brightness) is ~27 arcsec, for HIP 35210/35213 (HR 2764) and also for HIP 79043/79045 (HR 6008/6009), and the two largest that we accept provisionally as real are 7860 arcsec for α Cen (HR 5460) and ~7030 arcsec, for α PsA (HR 8728). The linear separation in α PsA is slightly more than 0.25 pc, and we can wonder whether such a system can survive even for one full rotation. The age of α PsA is estimated as 200 ± 100 Myr by Di Folco et al. (2004). If the two main bodies have been moving apart steadily over that interval, i.e. not orbiting but escaping, they have been doing so at the very low velocity of 0.0025 km s^{-1}, much less than the actual escape velocity. On the other hand, if they are orbiting, they have survived rather surprisingly for $\gtrsim$20 orbits of ~6 Myr each. But despite the uncertainty of such cases, we feel that only about 10 in (or not in) our entire sample are rather marginal either way.

Detection efficiency, such as the difficulty of observing long-period spectroscopic binaries and short-period visual binaries, will make the distributions of multiplicity, and of periods, differ from the true distribution. One of us (PPE) proposes to investigate this further using a Monte Carlo procedure that allows one to (i) construct a magnitude-limited sample of systems with multiplicity one to eight according to some hypothetical distribution of masses, ages, multiplicity and periods, and (ii) to 'theoretically observe' the members of this sample, making estimates of the efficiency of various observational procedures. This can map the original multiplicity into at least a lower limit to the observed multiplicity. It is difficult to believe that observations to date can constrain the number of T dwarf companions that an O star might have, but some less extreme pairings may be capable of being ruled in (or out).

Selection effects often interact with detection efficiency: if a given technique is known to work well for certain types of star, those types of star are more likely to be investigated with that technique. Thus, excellent radial-velocity orbits of quite long-period G/K binaries, say 1–30 yr, are known, but very few in this period range are known for O or B stars because their broad lines preclude measurement to the necessary accuracy. Nevertheless, there may be the same proportion of 1–30 yr binaries in both subsamples.

While the limits of various observing techniques in detecting binary companions can be modelled reasonably well, the extent of their application to our sample remains unexplored. For example, radial velocities of almost all bright stars have been measured several times, but the accuracy and time coverage vary to such an extent that we cannot apply uniform criteria to the sample as a whole. Many subsystems which are detectable spectroscopically still remain undetected. Similarly, only a fraction of bright stars has been observed interferometrically.

We note in Table 5 that the period distribution is bimodal at early spectral types, but unimodal, with a very broad maximum, at later types. That might be because the intermediate periods for O stars, 0.1–100 yr, are too close to recognize visually (although some are resolved), and too wide to recognize spectroscopically (although some also have been recognized). A preliminary version of the Monte Carlo code (Eggleton, Kisseleva-Eggleton & Dearborn 2007) suggested that the apparent bimodality of O-star periods can be explained this way; we should bear in mind the result (Table 6) that O stars appear to be more highly multiple than later stars, so that it can be not improbable for an O-star system to have at least three bodies, one pair of which might have a period in the 'missing' range.

There are indications in Table 4, or equivalently Fig. 1, that many multiples remain to be detected. On the one hand, the 4-mag-limited sample of Table 4 shows frequency N_n of multiplicity n dropping substantially less rapidly (roughly, $N_n \sim 2.3^{-n}$) than the 6-mag-limited sample (roughly, $N_n \sim 3.4^{-n}$). We would expect at most a small effect here. The brighter sample is on the whole nearer, so that visual multiples are more readily recognized, and biased to slightly more massive stars, which tend to be more highly multiple. But preliminary attempts at Monte Carlo modelling (Eggleton et al. 2007) suggest that this can only account for perhaps a third of the change in average multiplicity as seen between the two samples. We suggest that most of the difference is due to the fact that over the last three centuries the brightest stars have been studied most carefully.

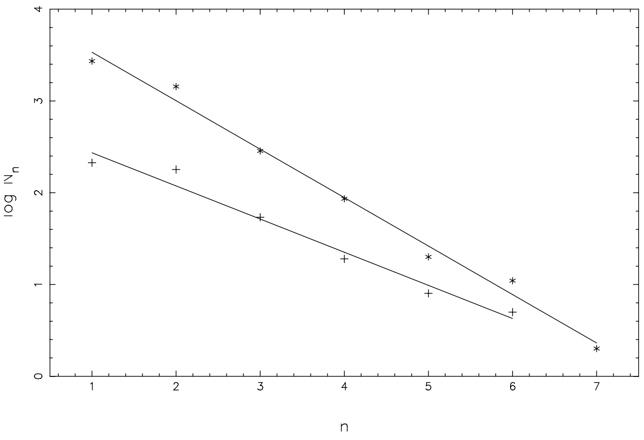

Figure 1. Log frequency as a function of multiplicity, from the first two lines of Table 1. Least-square fits are plotted, with slopes corresponding to −3.37 for the larger sample and −2.30 for the smaller sample.

Interestingly, this may now be the opposite of the truth. Modern detectors can so be sensitive that observers *avoid* the brightest stars.

The comparison of the northern and southern half-samples in Table 4 tells a possibly similar story. The fact that the northern sample has a modestly higher average multiplicity than the southern sample may be because the number of telescopes, and of observers, in the northern hemisphere has always been substantially larger. The difference between the northern and southern samples is not significant at the 99 per cent level, but it is significant (C. A. Booker 2008, p.c.) at the 95 per cent level, according to a χ^2 test. The preliminary Monte Carlo model of Eggleton et al. (2007) suggested that the true average multiplicity would have to be above 2.0 if the observed average multiplicity for the complete sample (top line of Table 2) is to be in excess of 1.5.

In Table 5, we do not discriminate between inner and outer periods, although it would not be difficult in principle to do so. Such discrimination would reveal that close pairs prefer to be inner components of higher multiplicity systems rather than pure $n = 2$ binaries. The present catalogue, as well as the MSC, contains rich information on the statistics of periods and mass ratios at different hierarchical levels.

6 DISCUSSION

We see three main areas where statistics of the multiplicity and period distributions for a complete magnitude-limited sample is potentially useful. First, they can constrain modelling of the star formation process. Star formation lacks any clear initial conditions, but at least it has some reasonably clear ‘final conditions’, and models can be tested against their ability to produce the kind of systems that are actually seen, in the right proportions. Secondly, the model can serve as the initial condition for subsequent nuclear evolution; and as we amplify below there is also the possibility of dynamical evolution within triples and higher multiples that can influence their nuclear evolution. Thirdly, we believe that such a model can also be helpful in computing the evolution of star clusters under the joint effects of nuclear evolution and *N*-body gravitational dynamics. Although the dense environment of those star-forming regions that generate clusters, i.e. that make a transition from a gas-dominated entity to a star-dominated entity of much the same size, is likely to prevent the existence of the widest multiples that our sample contains, it is a reasonable first hypothesis that the shorter period multiples will not be very different. If, in fact, an *N*-body calculation was started with statistical multiplicity as in our sample, presumably the wider systems would be rapidly broken up; but the closer systems could persist, and the presence of rather close primordial triples and quadruples would influence significantly the evolution of the cluster.

Regarding the second area, Eggleton & Kiseleva (1996) have enumerated a number of ways in which the existence of primordial triples can allow evolutionary channels that are different from what can be obtained from only binaries. We mention two here. First, triple stars in which the two orbits are misaligned can be subject to the dynamical effect of Kozai cycles (Kozai 1962), and these in turn can allow tidal friction to become important in the course of 10^6–10^9 yr and cause the inner orbit to become smaller (Mazeh & Shaham 1979; Kiseleva, Eggleton & Mikkola 1998; Eggleton & Kisseleva-Eggleton 2006). We call this process Kozai Cycles with Tidal Friction (KCTF). Tokovinin et al. (2006) have noted, using a maximum-likelihood method, that in a sample of spectroscopic binaries with periods <2.9 d, 96 ± 7 per cent have third bodies, as compared with 34 ± 6 per cent in the period range 13–30 d. Fabrycky & Tremaine (2007) have computed the effect of KCTF on a Monte Carlo ensemble of triples, and shown that indeed it can produce an accumulation at short inner periods. Pribulla & Rucinski (2006) have noted that as many as 42 per cent of contact binaries appear to be in triples (and arguably 59 per cent in a more thoroughly examined subsample), and it could be that KCTF has contributed to this; although we probably need the additional influence of magnetic braking, also with tidal friction (MBTF), to drive fairly close low-mass binaries generated by KCTF to contact on a time-scale of $\lesssim 10^9$. In our primary sample, line 1 of Table 4, there are 95 binaries with $P < 3$ d, and 60 of these are in systems with $n \geq 3$; this is a much higher proportion than for longer periods.

The second effect is the production of ‘anomalous binaries’. In short-period binaries, we can expect that a merger of the two components is a fairly common event. Case A systems can evolve conservatively only if the initial mass ratio is fairly mild ($1 > q \gtrsim 0.6$; Nelson & Eggleton 2001), and if q is not this mild then a merger seems quite a likely event. It would be hard to determine that a particular currently single star is a merged remnant of a former binary, although some Be stars that are apparently single might be such remnants. But within a primordial triple system, it is possible that such a merged remnant would be identifiable, because the wide binary that remains after the merger of the close subbinary would be expected, in at least some circumstances, to show an anomaly where the two components appear to be of different ages. R. E. M. Griffin (to be published) has found a number of such apparently anomalous systems, of which γ Per (HR 915) is an example. Although the mass ratio, obtained from careful deconvolution of the two spectra (G8II-III + A2IV; 5330 d, $e = .79$), is 1.54 (in the sense $M_\mathrm{G}/M_\mathrm{A}$), the A component seems surprisingly large and luminous compared with what it should be on the ZAMS; and it ought to be very close to the ZAMS if it is coeval with the G component. A possible explanation is that the giant is the merged product of a former subbinary with a mass ratio of ∼0.5, since this could allow the more massive two of the original three components to evolve at roughly the same rate (Eggleton & Kiseleva 1996). We hope to test shortly the possibility that the appropriate primordial triple parameters, from our Monte Carlo model, will give an acceptable number of potential progenitors. Alcock et al. (1999) and Evans et al. (2005) have noted that a similar process might lead to Cepheid binaries of an anomalous character, such as may be required to reconcile observed Cepheids with the theoretical models of the Cepheid pulsation phenomenon.

ACKNOWLEDGMENTS

This work was performed partly under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. We gratefully acknowledge the help of the Centre des Données Stellaires (Strassbourg) and the Astronomical Data System.

REFERENCES

Aerts C., Harmanec P., 2004, in Hilditch R., Hensberge H., Pavlovski K., eds, ASP Conf. Ser. Vol. 318, Spectroscopically and Spatially Resolving the Components of Close Binary Stars. Astron. Soc. Pac., San Francisco, p. 325

Alcock C. et al., 1999, AJ, 117, 920

Andersen J., Nordström B., 1983, A&AS, 52, 471

Batten A. H., Fletcher J. M., McCarthy D. G., 1989, Publ. Dom. Astrophys. Obs., 17, 1

Boffin H. M. J., Jorissen A., 1988, A&A, 205, 155

De May K., Aerts C., Waelkens C., Van Winckel H., 1996, A&A, 310, 164

Di Folco E., Thévenin F., Kervella P., Domiciano de Souza A., Coudé du Foresto V., Ségransan D., Morel. P., 2004, A&A, 426, 601

Dommanget J., Nys O., 2002, (CCDM) Observations et Travaux, 54, 5 (http://cdsweb.u-strasbg.fr/viz-bin/Cat?I/211)

Duqennoy A., Mayor M., 1991, A&A, 248, 485

Eggleton P. P., Kiseleva L. G., 1996, in Wijers R. A. M. J., Davies M. B., Tout C. A., eds, NATO ASI Series C, Vol. 477, Evolutionary Processes in Binary Stars. Kluwer, Dordrecht, p. 345

Eggleton P. P., Kisseleva-Eggleton L., 2006, Ap&SS, Vol. 304, p. 75

Eggleton P. P., Kisseleva-Eggleton L., Dearborn X., 2007, in Hartkopf W. I., Guinan E. F., Harmanec P., eds, Proc. IAU Symp. 240, Binary Stars as Critical Tools & Tests in Contemporary Astrophysics. Cambridge Univ. Press, Cambridge, p. 347

Evans D. S., 1977, Rev. Mex. Astron. Astrofis., 3, 13

Evans N. R., Carpenter K. G., Robinson R., Kienzle F., Dekas A. E., 2005, AJ, 130, 789

Fabrycky D., Tremaine S., 2007, ApJ, 669, 1298

Famaey B., Jorissen A., Luri X., Mayor M., Udry S., Djonghe H., Turon C., 2005, A&A, 430, 165 (http://cdsweb.u-strasbg.fr/viz-bin/Cat?J/A&bA/430/165)

Grenier S. et al., 1999a, A&AS, 137, 451

Grenier S., Burnage R., Faraggiana R., Gerbaldi M., Delmas F., Gómez A. E., Sabas V., Sharif L., 1999b, A&AS, 135, 503

Griffin R. F., 1998, Observatory, 118, 299

Harmanec P., 2001, Publ. Astron. Inst. Acad. Aci. Czech Rep., 89, 9

Hartkopf W. I., McAlister H. A., Franz O. G., 1989, AJ, 98, 1014

Hartkopf W. I. et al., 2000, AJ, 119, 3084 (http://cdsweb.u-strasbg.fr/viz-bin/Cat?J/AJ/119/3084)

Hoffleit D., Jaschek C., 1983, The Bright Star Catalogue, 4th edn. Yale University Observatory, New Haven (http://cdsweb.u-strasbg.fr/viz-bin/Cat?V/50)

Kiseleva L. G., Eggleton P. P., Mikkola S., 1998, MNRAS, 300, 292

Kozai Y., 1962, AJ, 67, 591

Lépine S., Bongiorno B., 2007, AJ, 133, 889

Lindroos K. P., 1985, A&AS, 60, 183

McClure R. D., 1983, ApJ, 268, 264

Makarov V. V., Kaplan G. H., 2005, AJ, 129, 2424 (http://cdsweb.u-strasbg.fr/viz-bin/Cat?J/AJ/129/2420) (MK)

Mazeh T., Shaham J., 1979, A&A, 77, 145

Nelson C. A., Eggleton P. P., 2001, ApJ, 552, 664

Nordström B., Andersen J., 1983, A&AS, 52, 479

Nordström B., Andersen J., 1985, A&AS, 61, 53

Parsons S. B., 2004, AJ, 127, 2915

Perryman M. A. C. et al., 1997, A&A, 323, 49 (http://cdsweb.u-strasbg.fr/viz-bin/Cat?I/239)

Pourbaix D. et al., 2004, A&A, 424, 727 (http://sb9.astro.ulb.ac.be/)

Preibisch T., Balega Y., Hofman K.-H., Weigelt G., Zinnecker H., 1999, New Astron., 4, 531

Pribulla T., Rucinski S. M., 2006, AJ, 131, 2986

Samus N. N., Durlevich O. V. et al., 2004, Combined General Catalogue of Variable Stars. Available at ftp://cdsarc.u-strasbg.fr/cats/II/250/

Simon M., Close L. M., Beck T. L., 1999, AJ, 117, 1375

Söderhjelm S., Mignard F., 1998, Observatory, 118, 365

Tokovinin A. A., 1997, A&AS, 124, 75 (http://www.ctio.noao.edu/atokovin/stars/index.php, 2007 version)

Tokovinin A. A., Thomas S., Sterzik M., Udry S., 2006, A&A, 450, 681

Verhoelst T. et al., 2005, A&A, 435, 289

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

Table 1. Configurations of bright multiple systems.
Table 2. Cross-reference table.
Table 3. Reference table.

This paper has been typeset from a TEX/LATEX file prepared by the author.