Multiple Stars in the Field

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Summary. When examining the statistics of multiple stars in the field, especially coming from visual binary star point of view, several problems present themselves. First, and most importantly, is distinguishing between physical multiples and optical pairs. Establishing physicality is not a simple "binary" response as there are degrees of certainty. We discuss some of the reasons for caring about non-physical pairs, as well as the tools for establishing or more correctly identifying apparent kinematic properties which hopefully result in dynamic solutions. The Washington Double Star Catalog, the Visual Orbit Catalog, and the US Naval Observatory speckle program are used as examples in many of these cases. The magnum opus for a global characterization of these systems is the Washington Multiplicity Catalog (WMC). Selected as a catalog and a method to "develop a simple, unambiguous, flexible, and computer friendly designation scheme for stellar companions (including planets)" at a multi-commission meeting in Manchester (GA24). This was re-affirmed at Special Session 3 in Sydney (GA25) by Commissions 5, 8, 26, 42, 45 and the Working Group on Interferometry when a sample (1/2 hour band) WMC was produced. An all-sky WMC is in progress the binary sources utilized in its construction and the implications resulting from it with regards to multiple stars in the field are discussed.

1 It's the WDS, not the WBS!

Double Stars are not necessarily Binary Stars![1]

1.1 Who cares about Doubles?

Since binaries are physical pairs and optical doubles are geometrical constructs, one may well ask: are doubles of any value, and if so, what? Distinguishing between these two has primarily been more a problem for imaging techniques than for other methods. For the WDS we keep track of doubles as well as binaries for several reasons:

- We don't know which doubles are binary. Characterizing a pair as a binary requires some sort of Keplerian arc to be distinguished or some other parameter

[1] While this talk will periodically focus on binaries rather than physical multiples, the same principles apply.

such as the system binding energy to be known. Until physicality is established many doubles are simply unknown possible pairs.

- We don't want to keep "discovering" new pairs. Once a pair is established as optical, retaining it in the databases but flagged it as optical can save resources spent chasing down possible binaries.
- The psf of imaging as well as spectroscopy and photometry are affected by unresolved pairs and the scattered light of wider pairs. For example, many doubles detected by Tycho were anomalous grid-step ghost doubles caused by scattered light from nearby bright stars.
- Differential proper motions from the WDS are often more accurate than those derived through more classical proper motion techniques [11]. This is due to the often much longer observational baseline, although the $\sqrt{N}$ improvement due to frequent observations is also a factor.
- Well characterized linear motion systems may be better scale calibrators than even definitive orbits.

1.2 Growth of the WDS

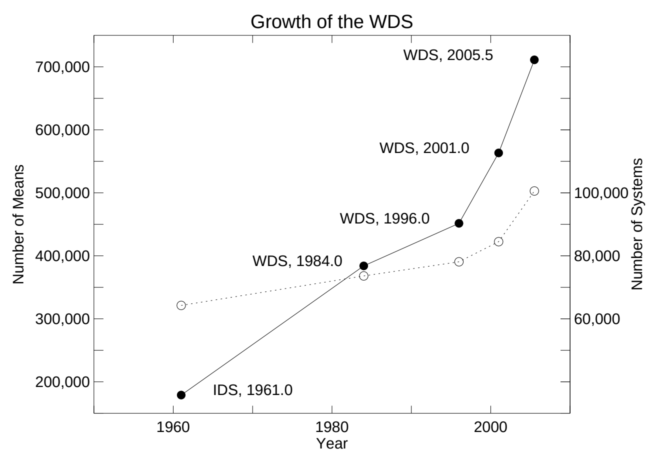

Fig. 1. Over the past twenty years the WDS has grown substantially: a 37% increase in numbers of systems (open circles) and an 85% increase in numbers of measures (filled circles). The first edition (1984) included 5.22 mean positions per pair. This number has improved with each subsequent edition (1996: 5.78 means/pair, 2001: 6.67 means/pair) to the current value of 7.11 mean positions per pair.

1.3 How do we find physical binaries and multiples?

There are a variety of methods for distinguishing between optical doubles/multiples and physical binaries/multiples. "Separating the wheat from the chaff" requires

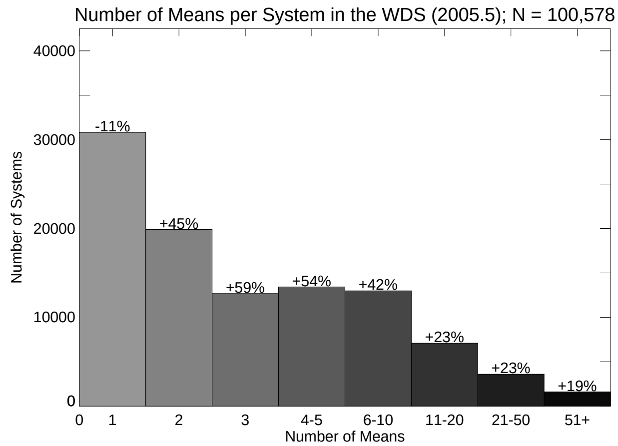

Fig. 2. The number of means per system, compared with the 1996 edition of the WDS. Despite the large number of new systems added to the catalog from Hipparcos, Tycho, etc. over the past 9 years, all bins except for the first have increased, as more systems have received follow-up observations.

some sort of parameter that characterizes a pair of stars as either gravitationally bound or chance alignment. These include:

- orbits (or some portion of a Keplerian arc),
- common proper motion (although pairs may be physically related, this relationship could be tenuous),
- common parallax (i.e., at the same approximate distance), and
- proximity (in other words, just close to each other in an angular sense).

2 Orbits

Absolutely, positively, without a doubt binaries (most of the time).

In addition to establishing physicality there are many compelling reasons for observing binaries to measure orbital motion — mass being the most obvious.

2.1 Combined Solution Orbits

The "best case" orbits are those which have gone through numerous revolutions. Sometimes, however, a small magnitude difference may result in two possible solutions (with periods $\sim P$ and $2P$). Other parameters can often help determine which solution is correct.

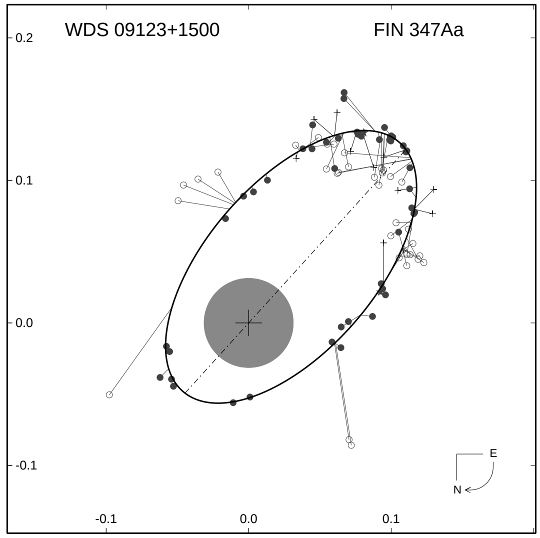

Fig. 3. Astrometric orbit plot of FIN 347 (= 81 Cancri), data 1959-2001, P = 2.7yrs., 14 rev. Scales are in arcseconds, and the large shaded region represents the resolution limit of a 4-m telescope. Filled and open circles indicate measures by speckle and eyepiece interferometry, respectively. See [13] for relative astrometry which uses the spectroscopic orbit from [5].

2.2 Preliminary Orbits

There are a variety of reasons, some scientific and others more sociological, why visual binary orbits are often calculated when orbital coverage is still marginal. The long orbital period relative to the scientist's career is a factor, but usually there is a compelling reason why the orbit should be calculated. Even with scant coverage, the astrophysically important derived parameter

$$3log(a) - 2log(P)$$

is often not grossly erroneous. Also, physicality is often ascertained from some other parameter, such as common parallax or proper motion, which would seem to indicate that any apparent motion may be more than "two ships passing in the night."

Regardless, many binaries have solutions which can be generously called "preliminary" and might more accurately be called "indeterminate" (or "nearly worthless"). The criteria for characterizing visual binary orbits are clearly spelled out in the *Sixth Catalog of Orbits of Visual Binary Stars* [7]. Figure 4 gives an example of a less well determined orbit.

3 Common Proper Motion

Are they binaries or are they simply members of the same moving group?

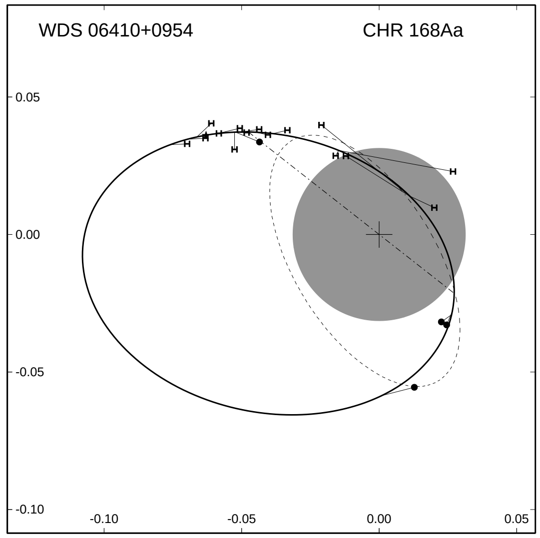

Fig. 4. Preliminary orbit of 15 Mon, from data taken with the CHARA and USNO speckle cameras, the Navy Prototype Optical Interferometer, and HST. The NPOI measure is a filled circle. Speckle measures are open circles (CHARA) or stars (USNO). HST-FGS measures are indicated by the letter **H**. The dot-dash line is the line of nodes, and the dotted ellipse is the orbit of [4]. The large shaded region represents the resolution limit of a 4-m telescope. HST measures were of noticeably lower quality in 1996-97 when FGS3 was in use. All later HST data were taken with FGS1r.

3.1 Proper Motion Doubles

The first known major survey for common proper motion (CPM) pairs was that of S.W. Burnham. He found 360 BUP pairs, which at present have an average of 4.14 measures/system. Since his work in the early part of the 20^{th} Century, 15 of them (4%) have been determined to have linear solutions and thus are likely non-physical doubles.

Around the middle of the last century H. Giclas and collaborators at the Lowell Observatory began an examination for additional CPM pairs. They found 197 GIC pairs (currently with 2.48 measures/system), all of which are apparently physical.

The greatest contribution, by far, was that of W.J. Luyten. Over the course of nearly 50 years he found 6,170 LDS pairs whose proper motion indicated they were related. Only two presently have linear solutions, which could be due either to better proper motions available to Luyten or (more likely) to the small number of observations to date (only 1.67 measures/system). This low observation rate is due to the faintness of targets and the difficulty in finding them. Due to the tireless work of Richard Jaworski [9], about $\frac{2}{3}$ of the LDS pairs now have modern $0\overset{''}{.}1$ positions and the number of measures per system will increase once these coordinates have been matched against other deep astrometric catalogs.

Recent work has been done by John Greaves using UCAC2 to look for CPM pairs. He has found 1143 GRV pairs thus far, but there is as yet only 1 meas/sys, limited to a portion of the Northern hemisphere. Before additional searches of this type are carried out it may be more appropriate to wait for the all-sky UCAC3, which will come out in 2006. Totalling about 60 million stars, UCAC3 will include final block adjustments and solutions for tens of thousands of doubles too close for earlier reduction. The expected precision of the proper motions will be primarily a function of magnitude: 2 mas/yr to 13^{th} mag and 4-6 mas/yr for those fainter.

Future proper motion work may include re-analysis of AGK2 data, now in process at USNO, which will supersede the AC data and give 1 mas/yr proper motion to 13^{th} mag for stars north of $2\overset{\circ}{.}5$.

4 Common Parallax

True Nearest Neighbors

Components of pairs with different parallaxes in the Hipparcos Catalogue were examined to see if they were actually close to each other. These included separate parallax values for Component (C) solution doubles in Vol. 10 of the Hipparcos Catalogue as well as the double entry systems. This work, done by USNO Summer Student Will Levine, defined pairs as physical if

$$|\pi_A - \pi_B| < \frac{3}{4}(\sigma\pi_A + \sigma\pi_B)$$

and optical if

$$|\pi_A - \pi_B| > \sigma\pi_A + \sigma\pi_B .$$

Following these criteria, 11,564 pairs were determined to be physical, with 234 optical and 6,998 indeterminate. Referring back to §2, four pairs with orbits of the lowest grade (5) have statistically different parallaxes and are probably optical.

5 Proximity

Binaries or physical multiples identified by compelling closeness.

The closer one “looks” for companions the less likely is the chance of random alignment. High-resolution techniques typically observe pairs with separations under an arcsecond, with some techniques reaching the sub-milliarcsecond level. The fact that these techniques, especially dilute aperture interferometry, are limited to the brightest (and preferentially closest) stars, decreases the odds of chance alignment even further. An example is HIP 40001, which was observed with the USNO speckle camera on the KPNO 4m telescope in January 2001, at a separation of 270 mas. At this separation and relatively small magnitude difference the chance of random optical co-alignment is small, but non-zero. While it can be argued statistically, the true physicality of the system can only be established through follow-up observations.

This sort of statistical culling of the BDS [2] was done by Aitken [1] during construction of the ADS catalog in the early 1930's. To avoid some of the problems described in §1.1 above, most of Aitken's rejected pairs were added back in by the time the IDS [10] was released. Retaining all pairs, but indicating physical or optical nature when possible, is the current modus operandi of the WDS [14].

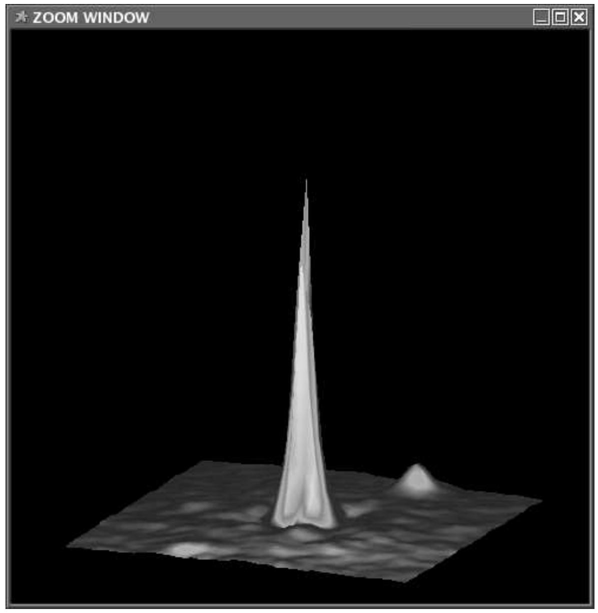

Fig. 5. HIP 40001 and its companion star.

5.1 Determining Physicality: Iota Ori

Arguments related to the physicality of close doubles are often made based on star counts and proximity. Since the true number of doubles is not known, these numbers, often based on observations by techniques with limited angular resolution, can undercount the true number of stars of a given magnitude. An example is ι Ori (= CHR 250Aa; see Figure 6). N-body simulations of the ι Ori / μ Col / AE Aur dynamical interaction [6] suggest that the speckle pair is extremely unlikely to be physical, despite the close angular separation.

6 The Washington Multiplicity Catalog (WMC)

an IAU sanctioned method for finding binaries and physical multiples from the vast number of catalogs that contain doubles

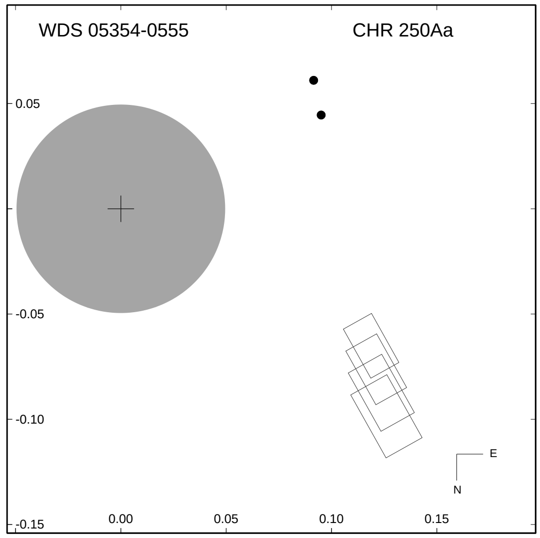

Fig. 6. At left is the double star CHR 250, with small filled circles indicating the 1994 and 1996 speckle measures reported in [12]. Scales are in arcseconds, and the large shaded circle represents the $0''.054$ resolution limit of the 100-inch telescope. The four small error boxes indicate the predicted location of the secondary in 2006.0, 2007.0, 2008.0, and 2009.0, assuming the motion is linear and both speckle measures are characterized by errors of $\Delta\theta = 0^\circ.5$, $\frac{\Delta\rho}{\rho} = 0.5\%$. Finding the companion within a box appropriate to the observation date would be a strong indication that the relative motion of the pair is linear (i.e., non-Keplerian) as has been suggested [6].

6.1 Roots of the WMC

Historically, double stars have been categorized by the method of detection: photometric, spectroscopic, or visual. This also generally corresponded to their periods, from shortest to longest, respectively. While this categorization did not always apply, the regions where these methods could overlap corresponded to a relatively few systems. However, because of the synergy of the techniques, these systems were often the most astrophysically important.

Each of the many techniques for investigating components to stars independently developed its own nomenclature scheme. While the separation/period regimes accessible to these different techniques remained mostly separate, the inconsistencies in these nomenclature schemes were of little consequence. However, with modern cross-correlation techniques detecting smaller ΔV_r systems with longer period and optical interferometry (first filled and later delute aperture) resolving shorter period systems, the historically disparate techniques are now seeing increasing overlap, with a commensurate increase in possibilities for component confusion.

The idea behind the Washington Multiplicity Catalog (WMC) was discussed in 1997 at the Manchester IAU-GA, as a means of addressing this nomenclature confusion. As many of these are multiple systems, there was also a desire for a flexible system which could retain hierarchical information.

Starting with the WDS nomenclature scheme, the WMC component designation was expanded through a series of lower case letters and numbers to take into account multiple hierarchies. At the Sydney GA in 2000 a sample WMC ($\frac{1}{2}$ hour of the sky) was presented which gave examples of the methods for addressing various nomenclature problems.

6.2 Applying WDS rules to the WMC

The WDS is a complete listing of all resolved systems (i.e., visual and interferometric doubles). There are an abundance of components to stars which are detected but not resolved (and are thus not in the WDS), however. These include:

1. spectroscopic doubles (single- or double-lined),
2. photometric or eclipsing binaries,
3. astrometric doubles (While not included in the WDS, several astrometric systems in the Orbit Catalog are given component designations as if they are resolved subcomponents, thus "reserving" these designations for their eventual resolution),
4. lunar occultation doubles,
5. contact systems and other doubles, and
6. planets.

6.3 Rules of Component Designation

The WDS at present extends nomenclature to second level hierarchies. The WMC will extend this nomenclature to cover more complex systems, however. Capital letter are used to indicate top level hierarchies (e.g., `012345.6+112233 AB`). Second- and third-level hierarchies are denoted by lower case letters (e.g., `Aa,Ab`) and numbers (e.g., `Ba1,Ba2`), respectively. Alternating lower case letters and numbers will be used to indicate progressively higher levels.. The coordinates used for the WMC are J2000, truncated to $0\overset{s}{.}1$ and $1''$ precision in RA and DEC, respectively.

6.4 Sources of Multiplicity

Since the majority of known doubles are visual pairs, the catalogs maintained at the USNO make an excellent starting point for the WMC. The following sources have been consulted:

- USNO Double Star Catalogs: WDS[14], ORB6[7], INT4[8], DM2[17]
- *A Catalog and Atlas of Cataclysmic Variables: On-line Version*,[2] [3]
- *Ninth Catalogue of Spectroscopic Binary Orbits*,[3] [15]
- *Catalog of Orbital elements, Masses and Luminosities of close double stars*, [16]
- California & Carnegie Planet Search website[4] and their links

[2] http://icarus.stsci.edu/~downes/cvcat/
[3] http://sb9.astro.ulb.ac.be/
[4] http://exoplanets.org/

6.5 Coordinate Matching

System matches are based on the stars arcsecond precise coordinates. The most time-consuming aspect of the WMC construction (by far!) has been the improvement of the WDS arcminute coordinates, which has been completed for more than 95% of these systems. Improvement of the remaining systems is on-going, although it will not be possible for some subset of these systems[5].

6.6 Multiplicity Statistics

Combining the WDS and other catalogs, then making a first pass at merging duplicate information (e.g., SB and EB pairs with two entries) yields 115,904 pairs. "Physicality" codes are assigned, as follows:

Code	Characterization	Source
P	"definitely" physical	systems with orbits, (incl. Hipparcos O systems), exoplanets, cataclysmic pairs
p	"probably" physical	astrometric/interferometric/occultation pairs, Hipparcos G systems, proximity (see text)
O	"definitely" optical	linear solution pairs
o	"probably" optical	proximity (see text)
C	"definitely" cpm	LDS, BUP, GIC, LPM, GRV pairs
c	"probably" cpm	similar proper motions, published comments, etc.
?	binarity uncertain	Hipparcos suspected non-singular, (X,S,V)
X	probably not real	plate flaws, misidentifications, etc

Other codes are assigned based on notes in the WDS and other catalogs. The remaining systems were assigned p or o code based on proximity:

$$log(\rho) = 2.8 - 0.2 \times V$$

with a minimum value of $2''$.

6.7 Grouping Pairs

Cluster members are flagged based on designations or proximity to known cluster members. The following pairs were removed:

- X and ? pairs: N=7,251
- Optical pairs: N=38,116
- Cluster members: N=543 (to get statistics for field stars)
- CPM pairs: N=7,811

The remaining pairs were checked for other entries within 3 arcmin in δ and $\alpha\cos(\delta)$ to differentiate simple binaries from multiples, then component designations are assigned for members of multiples.

[5] **You** try to find a 15^{th} (± 2) magnitude pair with arcminute-precision coordinates and unknown proper motion seen only once in the mid-19^{th} century! Other pairs are lost due to errors at the telescope or typographical errors in the original publications, while still others are misdentifications of photographic plate flaws, etc.

6.8 Results

Simple binaries: N=57,562
Multiple systems: N=1,901 (N=4,293 pairs)

Number of Components	Hierarchy Level 1	Hierarchy Level 2	Hierarchy Level 3
3	471	1101	0
4	44	134	56
5	9	29	19
>5	6	18	14

6.9 Results (including CPM pairs)

Simple binaries: N=62,005
Multiple systems: N=2,257 (N=5,069 pairs)

Number of Components	Hierarchy Level 1	Hierarchy Level 2	Hierarchy Level 3
3	650	1230	0
4	60	146	63
5	13	35	20
>5	7	19	14

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