Precise Stellar Radial Velocities
ASP Conference Series, Vol. 185, *1999*
J. B. Hearnshaw and C. D. Scarfe, eds.

Radial Velocities of Visual and Interferometric Binaries

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Abstract. We discuss the use of precise radial velocities for orbit studies of binary stars. Although they are desirable to achieve highly accurate masses for systems of large amplitude, their greatest value will be for systems of long period and low amplitude. These studies require high spectrograph stability, and in some cases resolution of the spectra may prove troublesome. Radial velocities must be combined with visual or interferometric observations for mass determination, since eclipsing binaries of long period are rare, but the number of resolved spectroscopic systems is increasing.

We review observational requirements, reduction techniques, and methods of solving for elements that satisfy simultaneously the observations in three dimensions, based on experience with radial velocities whose precision is near the lower limit for this Colloquium, obtained over the past 35 years with the Dominion Astrophysical Observatory (DAO) coudé spectrograph, and consider the gains that should be achievable over similar intervals in the future, by means of higher precision in all the relevant data. We discuss, from our own experience, the reasons why no masses have yet been determined by these methods, to an accuracy better than 2%.

1. Historical Introduction

At IAU Colloquia 5 and 62, 29 and 17 years ago respectively, one of us (Scarfe 1971, 1983) discussed the problem of radial-velocity observations of binary stars. Those Colloquia were sponsored by Commission 26, and thus were concerned primarily with binaries that were resolved visually or interferometrically, and hence of relatively long period. The second paper, an invited review, concentrated on three main areas, all of which remain relevant today; indeed one of them is the primary topic of this Colloquium. They were as follows:

1. The need for instruments of great long-term stability, and of a means of checking and confirming that stability.

2. The technique of cross-correlation, which had then been in use for fewer than 15 years, but is now widespread. Griffin's (1967) prototype instrument had established the technique, and the first CORAVEL of Baranne, Mayor, & Poncet (1979) had just begun its remarkable voyage of discovery.

https://doi.org/10.1017/S0252921100048715 Published online by Cambridge University Press

3. The use of comparison spectra impressed onto the starlight itself, and of polarization instruments, for obtaining very precise velocities. Such work was then only in its early stages, just eight years after Griffin & Griffin's (1973) first use of telluric lines, five years after Serkowski's (1976) polarization instrument, and two after Campbell & Walker's (1979) hydrogen fluoride cell.

At that meeting, several other papers were presented which we believe were important precursors to our present situation. McAlister (1983) reviewed the first five years of the wonderfully productive program of speckle interferometry conducted by the group at the Center for High Angular Resolution Astronomy (CHARA). Lacy (1983) produced the first, to our knowledge, stellar mass determination of accuracy significantly better than 1%, from an analysis of the light and radial-velocity variations of the eclipsing binary system YZ Cas. Batten (1983) discussed the important problem of reconciling disparate visual and spectroscopic orbital elements. And Davis (1983) discussed preliminary studies that have since then borne fruit in the Sydney University Stellar Interferometer (SUSI).

At Colloquium 88, which we were unfortunately unable to attend, Dravins (1985) discussed the limitations imposed by photospheric motions upon attempts to infer the motion of a star's center of mass from measurements made on its observed spectrum. These remain valid today, although the success of attempts to discover stars whose observed velocity is constant to better than 10 m s^{-1} indicates that such differences between the observations and the motion of the center of mass are sometimes constant, or at least variable only slowly, with a time scale measured in years, at that level of precision.

In another of Commission 26's Colloquia, number 135 in 1992, the substantial progress made, over the previous decade or so, in very precise radial-velocity measurement was elegantly and concisely reviewed by Walker (1992). He referred in particular to the efforts that had been made to ensure the stability of the various instruments in use, notably his own hydrogen fluoride cells and the iodine cells of Cochran & Hatzes (1990). A similar one is of course used by Marcy & Butler (1992), although over a longer wavelength region.

At the same meeting Morbey (1992) discussed the combination of radial-velocity data with those from visual and interferometric observations, arguing that it is really a straightforward matter to combine apples and oranges, provided that they are weighted by their dispersions. He also noted the existence of such powerful techniques as simulated annealing, arguing however that they are "overkill" for the relatively simple problem of combining angular data with radial velocities in solutions for binary orbits.

At that meeting too, a consensus developed to refer to the distance measurement that is a by-product of simultaneous angular and radial-velocity studies of the same system as its "orbital parallax". Despite the production of the marvellous Hipparcos catalogue since then, with its wealth of new and accurate parallax measurements, orbital parallaxes are the source of the most accurate stellar distances available today, although there remain few of them in the literature.

Another noteworthy paper presented at Colloquium 135 was that of Griffin (1992), who discussed the limited progress that had been made in bridging the

https://doi.org/10.1017/S0252921100048715 Published online by Cambridge University Press

gap between visual and spectroscopic binaries, despite the advent of speckle interferometry, and of efforts, largely his own, to pursue spectroscopic binaries with periods as long as a few decades. It is to be hoped that further advances in interferometry and patient pursuit of long-period systems will fill the gap more completely over the next several years. But the velocity amplitudes are so low in many cases that observations more precise than Griffin's will be required.

Then, too, the important tool of two-dimensional cross-correlation was introduced by Mazeh & Zucker (1992), with their two-dimensional correlation program TODCOR, subsequently described more fully by Zucker & Mazeh (1994). TODCOR has been put to good use by their colleagues at the Center for Astrophysics in deriving velocities of both components of a binary star from relatively noisy spectra. In particular Torres, Stefanik, & Latham (1997a, 1997b, 1997c) have applied it to binaries in the Hyades, including in the last of those three papers the difficult system θ^2 Tauri, for which they have made a valiant and plausible attempt to obtain the velocity amplitude of the rapidly-rotating secondary star. In the process they have obtained estimates of the mean distance to the cluster that should eventually become the standard value of that vital cornerstone of the astronomical distance scale. They have exercised commendable caution in seeking, and correcting for, systematic errors of as much as 4 km s^{-1} in the raw velocities produced by TODCOR, by means of synthetic spectra (Torres et al. 1997). There are many resolved binaries with two main-sequence components of similar brightness. The spectra of those of longer period are usually not resolved over a large fraction of their orbits; indeed they may never be free of blending. TODCOR appears to make a large selection of such objects amenable to study, so long as there is a modest velocity difference between the components. This may happen only for short time intervals near periastron passage, as was the case in one of its first uses (Torres 1995), on the 300-year binary Struve 248.

Since then too, we have followed the remarkable success of several groups in the detection of very low amplitude variations of radial velocity, sometimes ascribed to intrinsic variability, sometimes to the gravitational effect of orbiting objects of mass comparable to the giant planets. Indeed it appears that most, if not all, giant stars may show variations of a size now detectable. However, despite this progress, very few stellar masses of extremely high precision (better than 2%) have been published, and all of those have been derived from eclipsing systems. Why should this be so? And why should it matter?

2. Mass Determination for Visual-Spectroscopic Binaries

Let us consider the second question first. The combination of visual or interferometric observations with radial velocities permits the determination of two quantities vital for obtaining quantities of astrophysical significance from a binary star, which are not available from radial velocities alone. They are the orbital inclination and the system's parallax, the quantity to which we have referred above as the orbital parallax. This latter is available only if the system's mass ratio is known, either from astrometry or from measurement of both stars' radial velocities. Once these quantities are known, we can determine not only the stellar masses, but also their luminosities and the orbital angular momen-

https://doi.org/10.1017/S0252921100048715 Published online by Cambridge University Press

tum vector. As mentioned above distances found this way are often the most accurate of all such measurements, even for nearby objects with direct parallax measurements, including those from Hipparcos.

However the masses hitherto determined from such systems are at best accurate to little better than 3%, compared with about 0.5% for the best eclipsing binary solutions. This is regrettable, since as Andersen (1991) has pointed out, masses determined to better than 2% are required for critical tests of stellar models and stellar evolution theory. Andersen also points out that stellar radii of similar accuracy are available from eclipsing systems and not from resolved pairs. We would argue that luminosity is just as useful a parameter as radius, and is equivalent to it since of course they are related to each other via effective temperature. However although orbital parallaxes of visual-spectroscopic binaries are sometimes accurate to little more than 1% (see, e.g. Barlow, Fekel, & Scarfe 1993), and thus lead to very accurate values of the combined luminosity of the components, the individual luminosities are much less certain, since the determination of magnitude differences is notoriously difficult. Progress is being made even on that problem, however, for example by ten Brummelaar et al. (1996), who obtain magnitude differences with formal errors near 0.03 mag in R and as little as 0.01 mag in I. But in addition, for comparison with theory, bolometric luminosities are required, making it necessary to obtain magnitude observations in a wide range of bands. However, even this is not impossible. It has been done fairly well for Capella, for example (see Hummel et al. 1994, and references therein).

Why should we be unable to achieve the high precision described above? We would like to illustrate the problem from our own experience; thus in a sense this is a confession of failure! We have been observing with the coudé spectrograph of the DAO 1.2-m telescope since 1965, originally with photographic plates, since there was then no other choice. Since 1979, however, most of our observations have been made with the radial-velocity spectrometer (Fletcher et al. 1982, McClure et al. 1985). Despite the recent success of Skuljan, Hearnshaw, & Cottrell (1999) in reducing the uncertainties of observations made with that instrument, it has been our experience that they do not normally satisfy the minimum standard of precision, 300 m s^{-1}, required for this meeting, although the photographic velocities do.

It should be noted that those observations attest to the constancy of the instrument's zero-point, which is required for our purposes, rather than to absolute accuracy, which is not. An absolute scale requires observations of objects whose velocities can be calculated independently, and which illuminate the spectrograph's collimator in the same way as does starlight. Numerous fairly bright asteroids are suitable objects, particularly when the entrance slit is replaced by an image slicer (Richardson 1968) which scrambles the image. Optical fibers do this even better. However although we have obtained several observations of asteroids with the spectrometer, the insensitivity of photographic plates makes very difficult their use for asteroids (Scarfe 1985), among which only Vesta ever becomes brighter than magnitude $V = 6.0$.

Apart from M-type stars and most of those of luminosity classes I and II, whose intrinsic variability is detectable from photographic velocities, the r.m.s. scatter of such observations of IAU standards is pretty consistently 150 m s^{-1},

https://doi.org/10.1017/S0252921100048715 Published online by Cambridge University Press

over intervals as long as a quarter of a century (Scarfe, Batten, & Fletcher 1990, Scarfe 1997). Even when we began, however, such precision was nothing new, having been achieved at Mt. Wilson by Adams (1941) from three years of observations of Arcturus. In recent years we have heard claims of precisions 100 times better than anything achieved by such old-fashioned methods, but we have yet to see any substantiated, although Marcy, Butler & Fischer (1999) are getting close.

We have used an approach similar to that of Morbey (1975) in analysing orbits (Barlow & Scarfe 1991). We combine, in general, three sets of data, namely position angles, separations and radial velocities. Data in each set are weighted individually and in subgroups, the latter usually depending on their sources, to ensure that each subgroup gives the same standard error for an observation of unit weight. Then the three types of data are solved for the elements separately. If, and only if, the elements in common between them are in satisfactory agreement, is it reasonable to attempt a combined solution, although we are somewhat flexible in what constitutes satisfactory agreement! Otherwise it's back to observing! In any combined solution, the different sets of data are weighted relatively by the squares of the reciprocals of the standard errors of unit weight in the separate solutions. The combined solution should not increase those standard errors by an amount that is statistically significant, as a final test of the compatibility of the different kinds of data. We do not iterate these relative weightings; to do so would introduce bias in favor of the largest set of data.

3. Some Examples

Let us now give some individual examples of studies of a variety of illustrative objects, beginning with the single-spectrum systems ϵ Hydrae and ζ Herculis. We began observing ϵ Hydrae in 1965 with the short camera, but have followed it with the long one since 1968, when the mosaic grating was installed in the spectrograph, and presented interim reports at Colloquium 5 (Scarfe 1971) and just over a decade ago (Scarfe 1986). We have now just completed two orbital cycles with the long camera. ϵ Hydrae is a multiple system, and the 15-year binary's center of mass moves in an orbit with a more distant companion in a period of several centuries. According to a solution by Heintz (1963) the radial component of the motion in that orbit should be largest during the second half of the twentieth century. Thus our purpose in continuing the observations for so long has been to determine the sign of the inclination of the long-period orbit, which we have still not managed to do to our own satisfaction. Indeed we can detect no significant difference between the mean residuals in the first and second cycles; the standard deviation for an observation of unit weight is 0.19 km s^{-1} over the whole interval we have covered. The spectroscopic elements for the 15-year orbit agree satisfactorily with the visual/interferometric ones of Hartkopf, Mason, &McAlister (1996), however, and a simultaneous solution is planned.

R.M. Petrie began observing ζ Herculis photographically with the long camera of the coudé spectrograph in 1962, and now, over 32 years after his untimely death, we have followed it past the phase of his first observation in its 34.5-

https://doi.org/10.1017/S0252921100048715 Published online by Cambridge University Press

year orbit. The standard deviation for an observation of unit weight from the best-fitting orbit is 0.26 km s^{-1}. But again we detect only the primary component, and although its 4.0 km s^{-1} amplitude can be found from our data with an uncertainty of 0.8%, even if the secondary's amplitude could be found with equal precision, these two alone would cause the mass uncertainty to be over 2%. Moreover, although the eccentricity and argument of periastron now agree better with those found visually than did those we obtained 15 years ago (Scarfe et al. 1983), the discrepancy between the visual and spectroscopic values of the latter element still exceeds its formal error by a factor over seven, which is a cause for concern. To our chagrin the visual values of both elements, and of the time of periastron, are, as before, better determined than those from our radial velocities.

In 1983 we somewhat hesitantly obtained a combined solution, using our data and the visual normal points of Baize (1976), despite the discrepancies between the separate visual and spectroscopic ones, but its meaning, if any, remains unclear, because of obvious systematic trends in the residuals in position angle, separation and radial velocity. That disagreement indicated plainly that something was systematically wrong with one or more of the data sets, and raised doubts as to whether that solution had been worth obtaining. With the more complete coverage that we now have, and a significant increase in the available quantity of visual and interferometric data, we hope for better reconciliation in a new combined solution, to be obtained soon. In the meantime, we have run a solution which combines all our velocities with Baize's visual data. It does indeed give much more modest increases than formerly, from the individual solutions to the combined one, in the standard deviations for unit-weight observations of position angle, separation and radial velocity.

However, we are puzzled by the appearance of long systematic runs of radial-velocity residuals with predominantly the same sign, which suggest the presence of a secondary variation with roughly half the orbital period, and amplitude near 0.3 km s^{-1}. No such phenomenon can be seen in the residuals for IAU standard stars, or for ϵ Hydrae, over most of the same interval of time, so the effect does not appear to be instrumental in origin. But the period of the apparent secondary variation is so long as to make it very unlikely to be due to a third body, from stability considerations. Nor does a slowly varying stellar surface phenomenon seem likely, in view of the absence of reported photometric variability, and of the system's probable age.

Possible third bodies in ζ Herculis have a long history in the astronomical literature, however. The existence of such a body was suggested by Comstock (1917), but in his discussion of the spectroscopic orbit Berman (1941) said that the radial velocities then available did not support it. Underhill (1963) raised the matter again, but neither Lippincott (1981) nor Heintz (1994), gave much credence to it, and nor did we in our preliminary discussion (Scarfe et al. 1983). However Pan, Shao & Colavita (1992) suggested the possibility of a close companion 10 milliarcsec away; such an object's likely period would be only a few days.

The statistical significance of the long runs of residuals has been tested by performing a least-squares solution with our triple-system program (Barlow & Scarfe 1991), assuming that they have a sinusoidal time-dependence. The

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standard deviation of an observation of unit weight from that solution is only 0.22 km s^{-1}, a reduction from the result for the binary-only orbit solution which is highly significant according to an F-test. The amplitude of the sine wave is 316 ± 43 m s^{-1} and its period is almost 20 years. If we interpret it as being due to a companion, the latter's minimum mass is about 34 times the mass of Jupiter, with an uncertainty of about 20%. This places it near the minimum in the distribution of secondary masses proposed by Mazeh, Goldberg, & Latham (1999).

And yet stability considerations make us skeptical. We have not yet eliminated the possibility of there being a shorter period, which appears as a long one due to aliasing. But not many such periods are likely to be possible, given the number of observations and the fact that we have obtained them in every month of the year, and consequently at a wide range of hour angles.

Another possibility is suggested by the distribution of the residuals along the rising branch of the velocity curve, on which they change sign near the systemic velocity in a way suggestive of blending with the secondary star's spectrum, which would "drag" the measured velocity toward the systemic value. Although the difference in magnitude makes this unlikely, it cannot be ruled out at present, although it must be, before the behavior of the residuals can be attributed with confidence to a third body.

Both of those objects, especially ϵ Hydrae, have velocity amplitudes known to fairly high precision, and were the amplitudes of the secondaries similarly known, we could find quite accurate (around 1%) values of their mass ratios, and hence fairly reliable values of the individual masses of the components. There is of course a second way to obtain mass ratios, that of astrometry. But in general the images of such close and unequal pairs are single, and the astrometrist must resort to following the motion of the photocenter about the barycenter, in an orbit whose size seldom exceeds 1/4 that of the relative orbit of the two stars. The uncertainty of the mass ratio thus depends on the uncertainty of the angular size of that small orbit, and on that of the light ratio itself, which is seldom less than 0.1 magnitude. For a pair whose angular major semiaxis is known to 1% accuracy, and differing in brightness by 1.0 mag, determined with the above precision, and obeying a standard mass-luminosity relationship, it is easy to show that the mass ratio can be determined astrometrically to no better than 5%, which leads to mass uncertainties of 2% or 3% from that source alone.

The parallax π and mass ratio q of ζ Herculis, or more accurately the mass fraction B, where

$$B = \frac{M_2}{M_1 + M_2} = \frac{q}{1+q} \tag{1}$$

and

$$q = \frac{M_2}{M_1} = \frac{B}{1-B} \tag{2}$$

where M_1 and M_2 are the masses of the more massive and less massive stars respectively, were determined astrometrically by Lippincott (1981), and more recently by Heintz (1994). Their ratio π/B can be found from our combined solution, using

$$\frac{\pi}{B} = \frac{29.77\ a\ sin\ i}{KP\ (1-e^2)^{1/2}} \tag{3}$$

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where a is the major semiaxis in angular measure, i and e are the orbital inclination and eccentricity, P the period in years and K the velocity amplitude in km s^{-1}. The result agrees slightly better with that derived from Lippincott's data than did the one we obtained in 1983, and is once again substantially more precise than the astrometric one. Both spectroscopic results agree much better with that of Heintz, whom we believe to have taken better account of the effect of the secondary on the photocenter than did Lippincott. But the discrepancy between the astrometric and spectroscopic values is still over twice its own uncertainty. Moreover, about half of the uncertainty in the spectroscopic value comes from that of the velocity amplitude, and over a quarter of it from the angular major semiaxis. Clearly then there remains much to be done before we have a satisfactory solution to the orbit of even such a nearby and simple system.

A significant number of binaries contain giant stars, most of them in orbits with main-sequence companions. We still have relatively little information on the masses of giant stars, so these objects are particularly attractive for study. However, the giant often dominates the light to such an extent that the secondary spectrum is particularly hard to detect and measure. There are three situations, however, where it can be seen.

In the first case both components are giants. Evolutionary considerations lead us to expect that the mass ratio must be very close to unity for such systems, so close, indeed, as to make them rather rare. One well-known example, however, is Capella, which consists of a late G or early K giant, and a hotter star which lies in the Hertzsprung gap. The latter object is less massive and bolometrically less luminous than its cooler companion, despite being slightly brighter visually.

Barlow et al. (1993) published a solution for the orbit from new velocities, plus others published by Batten, Hill, & Lu (1991), combined with speckle interferometry and the classical work of Anderson (1920) and Merrill (1922). They determined the distance to the system to 1.1% but the masses only to about 3%. The uncertainty arises from the difficulty of measuring the hotter component's rotationally broadened spectrum, and from the orbital inclination, in roughly equal measure for the cool star's mass, although the inclination dominates the uncertainty of the hot star's mass, as can be seen from the first half of Table 1, which lists the percentage, of the variance of each parameter listed across the top, that is propagated from the uncertainty of each element given in the first column.

Table 1. Origin of Uncertainty for Capella.

Authors	Barlow	et al.	1993	Hummel	et al.	1994
Parameter	Parallax	Mass	Mass	Parallax	Mass	Mass
Star		Cool	Hot		Cool	Hot
Element						
Angular size a	24.4	–	–	2.1	–	–
Inclination i	46.2	49.4	72.9	2.4	1.6	4.2
Amplitude K(cool)	2.9	1.4	8.5	9.5	2.7	30.0
Amplitude K(hot)	26.5	49.2	18.6	85.9	95.7	65.8

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The work of Barlow et al. (1993) was used within a year by Hummel et al. (1994), whose more precise interferometry led to an even better-determined distance, and mass estimates with uncertainty under 2% for the hotter star, but not quite that small for the cooler star. They also measured the angular sizes of the components, with the result that we now know the radius and luminosity of the cooler star to better than 2%, but in those two quantities our knowledge of the hotter one lags behind, at just over 4% and 3% respectively. Moreover, the remaining uncertainty is now dominated by that of the velocity amplitudes, especially that of the hotter star, as shown in the second part of Table 1.

In the second case the companion is a hot main-sequence star, and the giant may often be above luminosity class III. The spectra are markedly different, and the group as a whole is described as having composite spectra. The hot component may be rotating rapidly, making its radial velocity very hard to determine. Indeed in a recent study of three such systems (Mason et al. 1997), no velocities of the secondary stars at all were published. And despite strenuous efforts with the Image Reduction and Analysis Facility (IRAF), Rosvick & Scarfe (1991) were unable to obtain as precise velocities of the hot component of α Equulei as they had hoped. It would appear, however, (Torres et al. 1997c) that TODCOR can permit at least some progress to be made on such difficult systems as these. And to be fair, the systems tackled by Mason et al. (1997) proved to be as difficult interferometrically as they were spectroscopically.

We note in passing that the U.S. Naval Observatory group has also resolved α Equulei (Armstrong et al. 1992), and used the radial velocities of Rosvick & Scarfe (1991), unsatisfactory as they are, to obtain preliminary values of the masses. But better observations of the secondary would be very worthwhile. We continue to follow the system sporadically, since it has shown residuals that lead us to suspect the existence of a third, more distant component.

In the third case the companion is a main-sequence star of type F or G, which is not so much fainter than the giant as to preclude its measurement when sufficiently resolved in radial velocity. Cross-correlation enables these faint companions to be picked out and measured even though their contribution to the total light is no more than 5%. One example is γ Canis Minoris (Scarfe 1995).

In summary, while we have made some progress, we would like to have made more. Our observations are fairly good, but better ones, over a similar long period, are required. Stable, preferably dedicated telescopes, are necessary for the success of such projects. Excellent techniques of reduction and analysis are required to get the most out of everyone's observations. But in the end, there is no substitute for good observational data, of all kinds, to provide the results that binary stars can yield for those who would challenge theoretical models. In particular, effort is required to obtain accurate determinations of velocity amplitudes for secondary stars, since at present these are the primary source of mass and parallax uncertainty more often than are any of the other observationally determined parameters needed to find those astrophysical quantities, despite the advantages they offer over astrometric determination of mass ratios.

We have not considered here triple systems, or those of higher multiplicity. They present a range of opportunities, and of challenges, that are beyond the scope of this paper.

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Acknowledgments. We have benefited enormously from discussions with many people over the years, and from collaboration with many others. Perhaps especially notable among these are Alan Batten, Murray Fletcher and Chris Morbey in Victoria, as well as Frank Fekel, plus Hal McAlister, Bill Hartkopf and their CHARA colleagues. And we recall with gratitude the long-ago encouragement to enter this field that was given by Robert Methven Petrie.

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Discussion

Popper: 1. One topic little discussed at this meeting is the effect of blending of the lines of the components, particularly for long-period, low-velocity-amplitude systems. 2. With respect to fitting models to observations of high precision, the dominant uncertainty may be that of the metallicity. 3. The use of radii in comparing evolutionary models with precise observations has the advantage over luminosity that radius always increases in the early stages of evolution, whereas temperature may change in either direction. Further the uncertainty in the temperature and hence in the luminosity may be considerably greater than in the radius.

Scarfe: 1. Blending is indeed a serious problem. It is possible that it is the source of the strange behavior we observe in ζ Herculis despite the large magnitude differnce. 2. The importance of metallicity is an issue whenever I discuss my results with Don VandenBerg. 3. Far be it from me to denigrate radii, but the difficulty with uncertain temperature scales applies whenever one tries to obtain luminosities from radii ... or vice versa!

Griffin: Determination of amplitudes for the secondary components of binaries is indeed important - I'm glad to hear that supported - but it is more difficult than 'just' pushing down the radial-velocity errors. Accuracy also enters; the confusion of overlapping spectra constitutes a serious contaminant. I have made some small progress in deriving amplitudes for secondary stars, but that progress is irritatingly slow. Binaries have fairly long periods, and one needs observations at critical dates, which a mere guest investigator finds particularly difficult to achieve. What we need is a dedicated telescope with a powerful spectrograph.

Scarfe: I agree; one gets pair-blending in many cases. Indeed in the case of γ Canis Minoris (Scarfe 1995), it is apparent as a distortion of the primary star's velocity curve, which should have led me to seek the secondary's "dip" long before it did.

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Lampens: An important by-product of combining spectroscopic and interferometric data for orbits is an independent check of the Hipparcos parallaxes for binary systems.

Scarfe: I agree. We have a paper on 12 Persei (Barlow, Scarfe, & Fekel 1998) in which we obtain an orbital parallax which agrees with that from Hipparcos within the latter's uncertainty; our own uncertainty is smaller by a factor of 2 or 3.

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