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A SPECTROSCOPIC ORBIT FOR HR 152

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HR 152, one of the four reference stars used to standardize radial-velocity observations made at Cambridge, has been shown by measurements made with the Dominion Astrophysical Observatory radial-velocity spectrometer to be a spectroscopic binary. The effects of its variability are traceable in the residuals of many spectroscopic-binary orbits based on Cambridge data. The orbit has a period of 576 days and a semiamplitude of 0.69 ± 0.08 km s^{-1}; this is the first plausible orbit to be published with a semiamplitude smaller than 1 km s^{-1}.

Key words: radial velocities—spectroscopic binaries—orbits—stars, individual

I. Introduction

It is nearly 20 years since the principles of the photoelectric radial-velocity spectrometer (Fellgett 1953) were first demonstrated in an operational instrument at Cambridge (Griffin 1967). The technique made it possible for the first time to obtain measurements of radial velocity at the 1 km s^{-1} level of accuracy for large numbers of stars fainter than the sixth magnitude.

The procedures used at Cambridge, where the prototype spectrometer is still in active use, differed in several important respects from those normally employed in photographic radial-velocity observations. The particular matter that concerns us here relates to the method of standardization of the velocities. Whereas stellar velocities are conventionally referred to a laboratory source of emission lines, such as an iron arc, the Cambridge procedure called for velocities to be measured differentially between one star and another. This necessitated the adoption of a number of "reference", i.e. standard, stars whose velocities were supposedly known and constant. The minimum number of reference stars compatible with the requirement that at least one should be accessible at a reasonable zenith distance at all times was deemed to be four. Four fifth-magnitude late-type giants at declinations of $+35° \pm 10°$ and at approximately six-hour intervals of right ascension were selected: they were HR 152, 63 Aurigae, 41 Comae Berenices, and λ Lyrae.

One of the first tasks (Griffin 1969) undertaken with the Cambridge photoelectric instrument was to determine the relative and absolute velocities of the reference stars, through careful intercomparisons of their velocities one with another and with those of a considerable number of other stars supposed (Wilson 1953) to have accurately known velocities. Through a combination of inexperience and misfortune, that important preliminary work was significantly defective, as has by degrees become apparent (Griffin and Herbig 1981; this paper). The standard deviation of a single intercomparison between reference stars was 0.6 km s^{-1}, which at the time seemed to be a very satisfactory accuracy. No velocity variations were identified in any of the reference stars; but in retrospect it is obvious that the observations were not by any means sustained over a long enough interval—the very same shortcoming as was criticized (Griffin 1975) when it was exhibited by others (Heard and Fehrenbach 1972)! Comparisons among the reference stars and between them and other standards of radial velocity were not maintained after the initial work was completed. It was expected that if any change ever occurred in the velocity of a reference star, it would be manifest as an apparent reflex variation of all stars on the Cambridge observing program in the whole quadrant of the sky that depended upon that reference star.

Standards of radial-velocity accuracy have been further improved in some of the spectrometers built after the Cambridge one (Griffin and Gunn 1974; Baranne, Mayor, and Poncet 1979; Fletcher, Harris, McClure and Scarfe 1982), and standard deviations of 0.2 to 0.4 km s^{-1} are now routinely achieved. Other instruments, most of them also based on the principle of cross-correlation but using multielement electronic detectors to observe the spectrum which is then correlated digitally with a numerical mask, have achieved still higher accuracy in limited contexts. Indeed, several groups (Campbell and Walker 1979; Reay, Ring and Pietraszewski 1983, Merline and McMillan 1985, Cochran and Smith 1985) aim to obtain accuracies sufficient to detect planetary systems around stars other than the sun through the reflex motions of the stars concerned. To detect Jupiter by radial-velocity observations of the sun would involve the establishment of an orbit with amplitude $K \simeq 13$ m s^{-1}. There is, however, at present a hundredfold gap between such an aim and what has actually been achieved in the field of spectroscopic binaries: the smallest amplitude yet documented with tolerable reliability is that of the orbit established (Griffin 1985) with the Cambridge spectrometer for 6 Bootis, with $K \simeq 1.2$ km s^{-1}.

II. HR 152

HR 152 (HD 3346), one of the Cambridge reference stars, is a fifth-magnitude object about 3° north preceding the Andromeda nebula. Its broad-band magnitudes have been given by Argue (1966, 1967) as $V = 5^{m}.13$, $(B-V) = 1^{m}.60$, $(U-B) = 1^{m}.97$, and $(R-I) = 0^{m}.95$. Its spectrum has been classified on the MK system as type K5 III (Roman 1952) and "K5 to M0 III" (Keenan and Pitts 1980).

The radial velocity of HR 152 was first measured by Adams and Joy (1923), who obtained a value of -31.2 ± 2.0 km s^{-1} from four plates taken at the Cassegrain focus of the Mount Wilson 60-inch (1.5-m) reflector with a prism spectrograph giving a dispersion of 36 Å mm^{-1} at Hγ. Campbell and Moore (1928) obtained velocities of -32.9, -32.8, and -34.0 km s^{-1}, respectively, from three plates taken in 1920–21 with the Mills Spectrograph on the Lick 36-inch (91-cm) refractor, where the dispersion was 11 Å mm^{-1} at λ 4500 Å. The velocity adopted for reference purposes at Cambridge (Griffin 1969) was -32.6 km s^{-1}, which seemed to be in good agreement with the earlier determinations.

Remeasurement of the Cambridge reference stars with the radial-velocity spectrometer 'Coravel' (Baranne et al. 1979), which employs a laboratory reference source to give the zero point, indicated that a systematic correction of -0.8 km s^{-1} was needed to the Cambridge reference-star velocities but did not identify any variability (Mayor, private communication, 1979). The need for such a correction was supported by the discussion of Griffin and Herbig (1981). Meanwhile, the spectrometer at the Dominion Astrophysical Observatory, Victoria (Fletcher et al. 1982) was brought into operation, and the Cambridge reference stars were intensively observed with it. As time went on, the Victoria observations first showed with increasing conviction that HR 152 varied in velocity, and then indicated a periodicity of about 600 days.

In 1983 this discovery was communicated to Cambridge. Few stars of constant velocity had been repeatedly observed at Cambridge, so no check was available in that way. Nevertheless, it proved possible to verify immediately the variation in the velocity of HR 152, as it was traceable in the residuals of spectroscopic-binary orbits determined in Cambridge for that part of the sky for which HR 152 serves as the reference star.

III. HR 152—Observations and Orbit

Observations of HR 152 with the Victoria spectrometer do not cover a sufficient number of cycles of the velocity variation, the period for which we shall show below to be about 570 days, to define the period with high accuracy. An accurate period is needed if the phase of the variation is to be known throughout the interval when HR 152 has been used for reference purposes at Cambridge. Two avenues of approach are open to us in our efforts to refine the period; they are described in the following paragraphs.

First, we can use the residuals from Cambridge orbits which depend upon HR 152 as the reference star. By treating the residuals as if they were ordinary velocity data, we can reveal in them a periodicity which leads to an apparent orbit related to that of HR 152. In the orbit derived from the residuals, the γ-velocity is expected to zero, and the velocity scale is evidently inverted with respect to that for HR 152. Also, the amplitude will be somewhat smaller than the amplitude of HR 152 itself: in the individual orbits which yielded the residuals used here as our input data, the computed solutions will have accommodated to some extent the errors introduced by variations in the reference star.

The spectroscopic binaries whose orbits have been or soon will be published from Cambridge and whose right ascensions are within two hours of that of HR 152—guaranteeing that that reference star was used almost (if not quite) exclusively—are listed in Table I. In the published orbit of longest period, that of HD 222018, which also happens to have high eccentricity so there is a long interval during which the velocity changes are very slow, the effects of variation of the reference star are visible directly as an oscillation of the observed velocities about the mean curve. Binaries whose periods are close enough to that of HR 152, in relation to the total time span over which they were observed, will have had their orbits influenced by the variation of HR 152 in a way that runs systematically with phase. The orbital elements determined for those systems may have been appreciably affected by the variation, and their residuals may therefore be uninstructive. The same may be true at periods close to twice that of HR 152. Such orbits are noted in Table I and are not

TABLE I
Spectroscopic binary orbits depending on HR 152

Star identification Name	HR	HD	Period (days)	Reference
		2343	936	Observatory 99, 87, 1979
		7272	1969	M.N.R.A.S. 210, 745, 1984
		7308*	660	J.R.A.S. Canada 74, 348, 1980
		9313	54	Observatory 95, 98, 1975
		9828	183	M.N.R.A.S. 201, 487, 1982
ξ Psc	549	11559	1672	M.N.R.A.S. 196, 33, 1981
		11579	1629	Observatory 99, 124, 1979
	551	11613	838	Observatory 101, 175, 1981
	616	12923	5300	In preparation
60 And	643	13520	748	M.N.R.A.S. 196, 33, 1981
ξ^1 Cet	649	13611	1642	M.N.R.A.S. 196, 33, 1981
		13725	693	Observatory 103, 284, 1983
		13738*	1385	Observatory 97, 196, 1977
		14346	100	Observatory 105, in press
		14969	1935	M.N.R.A.S. 190, 711, 1980
		14985	857	Observatory, in preparation
		220007	1520	Observatory 99, 198, 1979
		222018	3234	Observatory 104, 189, 1984
		223969	740	Observatory 97, 86, 1977
		224118*	1205	Observatory 104, 80, 1984
		225292	954	J.R.A.S. Canada 75, 222, 1981

*Not used: period too nearly commensurable with that of HR 152

considered further in this investigation, although it will be useful to recompute them with the data corrected for the variation of the reference star. The velocity curve derived from the residuals of Cambridge observations of all the remaining stars listed in Table I is shown in Figure 1 and has the elements given in the middle column of Table II.

The second means at our disposal to refine the period of HR 152 is the conventional one of utilizing early data. The 'Coravel' measurements extend the time base of the observations considerably. In addition, we have four velocities derived from Victoria 2.4 Å mm^{-1} photographic spectrograms dating from 1969 and 1970. They were obtained in partial response to a request made by Griffin to the then Director of the Dominion Astrophysical Observatory, Dr. K. O. Wright, following the latter's claim (Evans 1970) to be able to obtain velocities of late-type stars down to seventh magnitude with an external error of 0.1 km s^{-1}. A complete list of the velocities available to us is given in Table III, and the orbital elements derived from them appear in the last column of Table II. Figure 2 shows the orbital solution graphically.

Since the two series of data which give rise to the two sets of elements listed in Table II are totally independent of one another, the close correspondence between the periods found from them is encouraging. To obtain the best orbit from the various solutions, however, is not entirely straightforward.

The first question to which we must address ourselves is whether the eccentricity found for the orbit is really significant or not. Comparison of the eccentricities given

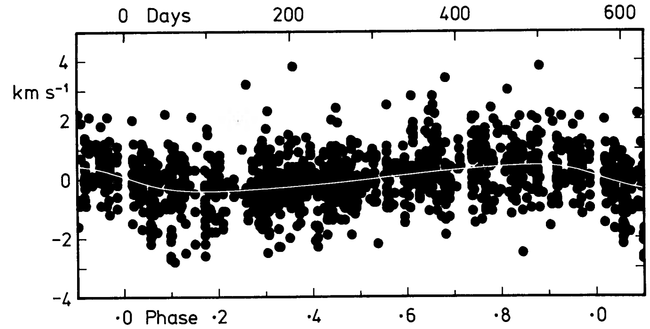

FIG. 1—Residuals of Cambridge observations used in the determination of the spectroscopic-binary orbits listed in Table I. The residuals have been treated as if they were normal radial-velocity data and have yielded a period of 572.6 days, upon which they are phased in the figure. The white line indicates the computed apparent orbit, which reflects the variation of velocity of the reference star HR 152. The elements of this orbit are given in the middle column of Table II.

TABLE II
Orbital elements for HR 152

Element	Source of radial-velocity data: Residuals from Cambridge orbits	DAO-Coravel observations
P (days)	572.6 ± 4.4	581.0 ± 6.0
γ (km s^{-1})	+0.01 ± 0.03	−33.62 ± 0.05
K (km s^{-1})	0.43 ± 0.04	0.69 ± 0.08
e	0.32 ± 0.08	0.26 ± 0.11
ω (degrees)	83 ± 19	308 ± 25
T (MJD)	43190 ± 26	44985 ± 38
No. of data	1068	104
R.m.s. residual (km s^{-1})	0.87	0.54

in Table II with their standard errors suggests that it *is*, but a more reliable discriminant is provided by the statistical tests given by Bassett (1978). When zero eccentricity is forced upon the solution of the Cambridge data, the sum of the squares of the (now second-order) residuals is increased from 811.95 (km s^{-1})^2, for the orbit shown in Table II, to 818.36 (km s^{-1})^2. Bassett's two tests both show that the increase is significant at the 2.5% level, though not at 1%. Thus it seems very likely that the orbit is indeed noncircular. The circular orbit from the Victoria-Coravel data has a sum of squared residuals of 32.71 (km s^{-1})^2, compared with the 30.83 for the orbit whose elements are listed in Table II. Bassett's statistic T_1 shows the difference to be just significant at the 5% level; T_2 falls between 10% and 5%. Another useful comparison is that between the two values of ω. Remembering that the solution given in the middle column of Table II is that of residuals and is therefore inverted with respect to the orbit of HR 152 itself, we see that the Cambridge-based orbit has ω = 263° ± 19° while the Victoria-Coravel one ω = 308° ± 25°: the difference is 45°, which is tolerable both absolutely and with respect to its standard error of 31°. Therefore we conclude, on the basis of (a) the

TABLE III
Radial-velocity observations of HR 152

Date	MJD	Velocity km s^{-1}	Phase	(O - C) km s^{-1}	Obs.*
1970 Aug 4.43	40802.43	-33.9	0.801	+0.2	Pg
9.47	807.47	-34.4	.809	-0.3	Pg
1971 Aug 26.45	41189.45	-33.9	1.467	0.0	Pg
29.39	192.39	-33.3	.472	+0.5	Pg
1977 Sept 10.0	43396.0	-33.8	5.265	-0.5	Cor
18.0	404.0	-33.9	.278	-0.6	Cor
Oct 18.0	434.0	-33.7	.330	-0.2	Cor
1978 Aug 18.1	43738.1	-33.9	5.853	+0.1	Cor
Sept 15.0	766.0	-33.4	.901	+0.3	Cor
Oct 1.0	782.0	-33.8	.929	-0.2	Cor
14.0	795.0	-33.1	.951	+0.3	Cor
26.9	807.9	-33.8	.974	-0.5	Cor
Nov 22.8	834.8	-32.8	6.020	+0.2	Cor
1981 Mar 5.12	44668.12	-34.4	7.454	-0.6	DAO
13.12	676.12	-35.0	.468	-1.1	DAO
20.13	683.13	-34.6	.480	-0.7	DAO
June 26.48	781.48	-34.8	.649	-0.6	DAO
Aug 1.50	817.50	-35.6	.711	-1.4	DAO
14.50	830.50	-33.7	.734	+0.5	DAO
28.51	844.51	-33.9	.758	+0.3	DAO
Sept 2.51	849.51	-33.9	.766	+0.3	DAO
14.52	861.52	-34.0	.787	+0.2	DAO
29.42	876.42	-35.0	.813	-0.9	DAO
Oct 2.27	879.27	-34.3	.818	-0.2	DAO
Nov 8.17	916.17	-34.3	.881	-0.5	DAO
27.37	935.37	-33.6	.914	+0.1	DAO
30.29	938.29	-33.5	.919	+0.2	DAO
1982 Feb 9.14	45009.14	-33.2	8.041	-0.3	DAO
18.10	018.10	-33.4	.056	-0.6	DAO
19.21	019.21	-33.5	.058	-0.7	DAO
Mar 18.15	046.15	-33.0	.105	-0.2	DAO
19.14	047.14	-33.2	.106	-0.4	DAO
23.14	051.14	-32.6	.113	+0.3	DAO
Apr 8.16	067.16	-31.7	.141	+1.2	DAO
9.54	068.54	-32.0	.143	+0.9	DAO
May 5.49	094.49	-33.2	.188	-0.1	DAO
23.47	112.47	-33.9	.229	-0.8	DAO
July 11.48	161.48	-33.6	.303	-0.1	DAO
19.48	169.48	-33.6	.317	-0.1	DAO
21.50	171.50	-33.4	.321	+0.1	DAO
22.51	172.51	-34.4	.322	-0.9	DAO
28.48	178.48	-33.1	.333	+0.4	DAO
Aug 17.45	198.45	-34.4	.367	-0.8	DAO
18.52	199.52	-34.3	.369	-0.6	DAO
19.52	200.52	-33.3	.370	+0.3	DAO
20.48	201.48	-32.9	.372	+0.8	DAO
24.48	205.48	-33.1	.379	+0.5	DAO
25.56	206.56	-33.6	.381	+0.1	DAO
26.50	207.50	-33.3	.382	+0.3	DAO
Sept 3.44	215.44	-33.1	.396	+0.5	DAO
16.0	228.0	-33.6	.418	+0.1	Cor
1982 Oct 5.19	45247.19	-34.1	8.451	-0.3	DAO
10.57	252.57	-34.1	.460	-0.3	DAO
12.41	254.41	-33.5	.463	+0.4	DAO
19.39	261.39	-34.4	.475	-0.6	DAO
28.9	270.9	-33.8	.492	+0.1	Cor
Nov 10.39	283.39	-33.6	.513	+0.4	DAO
15.9	288.9	-33.6	.523	+0.4	Cor
1983 Jan 14.07	45348.07	-34.0	8.624	+0.1	DAO
19.07	353.07	-34.3	.633	-0.1	DAO
Feb 1.20	366.20	-34.7	.656	-0.5	Pg
19.10	384.10	-34.0	.686	+0.2	DAO
Mar 17.13	410.13	-33.6	.731	+0.6	DAO
Apr 16.53	440.53	-33.5	.784	+0.7	DAO
17.53	441.53	-34.3	.785	-0.2	DAO
28.52	452.52	-34.5	.804	-0.3	DAO
May 12.50	466.50	-34.2	.828	-0.1	DAO
20.48	474.48	-33.8	.842	+0.2	DAO
June 14.46	499.46	-33.7	.885	+0.1	DAO
July 19.50	534.50	-33.4	.945	0.0	DAO
Aug 7.1	553.1	-33.0	.977	+0.2	Cor
13.47	559.47	-33.3	.988	-0.1	DAO
14.49	560.49	-32.4	.990	+0.8	DAO
Sept 5.0	582.0	-32.8	9.027	+0.1	Cor
6.40	583.40	-32.9	.029	0.0	DAO
11.1	588.1	-32.9	.038	0.0	Cor
20.49	597.49	-32.3	.054	+0.5	DAO
28.41	605.41	-32.1	.067	+0.8	DAO
29.38	606.38	-32.9	.069	-0.1	DAO
30.50	607.50	-32.9	.071	-0.1	DAO
Oct 1.55	608.55	-34.0	.073	-1.2	DAO
5.44	612.44	-33.4	.079	-0.6	DAO
11.55	618.55	-33.3	.090	-0.5	DAO
15.22	622.22	-31.6	.096	+1.2	DAO
29.27	636.27	-32.9	.120	0.0	DAO
Nov 9.9	647.9	-33.1	.140	-0.2	Cor
29.41	667.41	-33.0	.174	0.0	DAO
Dec 1.16	669.16	-33.1	.177	-0.1	DAO
28.25	696.25	-32.8	.224	+0.3	Pg
1984 Jan 11.8	45710.8	-32.4	9.249	+0.8	Cor
13.07	712.07	-33.1	.251	+0.1	DAO
Feb 1.09	731.09	-33.4	.284	0.0	DAO
17.11	747.11	-33.9	.311	-0.5	DAO
May 29.47	849.47	-32.2	.487	+1.7	DAO
June 1.47	852.47	-33.8	.493	+0.1	DAO
July 13.1	894.1	-34.7	.564	-0.6	Cor
Aug 3.50	915.50	-33.2	.601	+0.9	DAO
19.43	931.43	-34.2	.628	-0.1	Pg
26.30	938.30	-35.2	.640	-1.0	DAO
28.53	940.53	-33.9	.644	+0.3	DAO
30.1	942.1	-34.2	.647	0.0	Cor
30.53	942.53	-33.6	.648	+0.5	DAO
Sept 6.1	949.1	-33.6	.659	+0.6	Cor
17.35	960.35	-33.5	.678	+0.7	DAO

*Observatory code: Pg = DAO photographic observation (2.4 Å mm^{-1}); Cor = Coravel; DAO = DAO spectrometer. The Coravel observations, initially on the system of the IAU faint standards (Pearce 1957), have been corrected by +0.6 km s^{-1}. The DAO photographic observations have been accorded double weight.

values found for the eccentricity in relation to their own standard deviations, (b) Bassett's (1978) statistical tests, and (c) the reasonable agreement of e and ω for the orbits derived from two entirely independent series of data, that the evidence for nonzero eccentricity in the orbit of HR 152 is fairly compelling.

It remains to obtain the best mean values from the results given in Table II. The Cambridge orbit has no

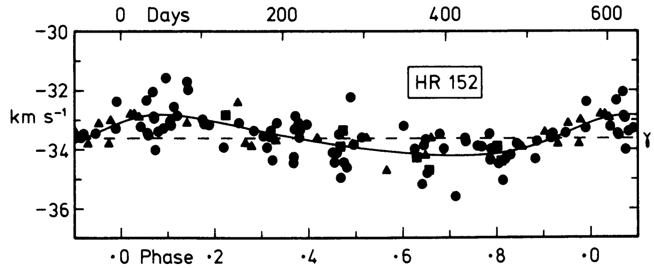

FIG. 2—The computed radial-velocity curve for HR 152, with the velocities observed at Victoria and with 'Coravel' plotted. Squares represent photographic, and circles photoelectric, measurements made at the Dominion Astrophysical Observatory; triangles denote 'Coravel' photoelectric velocities.

information about the γ-velocity, and for that quantity we rely entirely upon the Victoria velocities. As noted in Table III, the Coravel velocities have been adjusted by a far-from-trivial amount (+0.6 km s^{-1}) to bring them into systematic accord, so our adopted γ-velocity is 0.6 km s^{-1} higher than would be expected from the Coravel velocities alone. Differences of zero point can easily arise from the use of different standard stars, since the constancy, accuracy, and homogeneity of the velocities of even IAU standard stars are nothing like good enough for the standardization of modern photoelectric radial velocities. This matter is receiving urgent attention by a number of investigators, including some of the authors of this paper (Batten et al. 1983; Mayor and Maurice 1985), but we cannot attempt to resolve it here; we simply note that the γ-velocity here adopted is intended to be on the "Victoria RVS" system of Fletcher et al. (1982).

The amplitude of velocity variation given by the Cambridge residuals is, as expected, rather smaller than that found from direct observations of HR 152 and is of no significance in itself, so the amplitude is taken from the Victoria-Coravel data. We have thought it appropriate to take mean values of P, e, and ω, weighted inversely as the variances of the individual quantities concerned. The value of T is also a mean, but allowance has of course had to be made for the effect of altering ω from the initially computed values as well as for the solutions referring to different epochs. The finally adopted orbital elements are given in Table IV.

Now that the orbit of HR 152 has been determined, there is no reason (apart from inconvenience) why that star should not continue to be used for reference purposes at Cambridge and elsewhere. The large number of already-existing Cambridge observations which depend on HR 152 as the reference star will be corrected for its variation before publication.

TABLE IV
Finally adopted orbital elements for HR 152

P = 576.2 ± 3.5 days	T = MJD 43787 ± 22
γ = −33.62 ± 0.05 km s^{-1}	K = 0.69 ± 0.08 km s^{-1}
e = 0.30 ± 0.06	ω = 279 ± 15 degrees
$a_1 \sin i$ = 5.1 ± 0.6 Gm	f(m) = (17 ± 5) × 10^{-6} $M_\odot$

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