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Spectroscopic Binaries near the North Galactic Pole Paper 12A: 6 Boötis

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Abstract. About 25 years ago, in Paper 12 of this series, the author presented a spectroscopic orbit for 6 Boo. The velocity amplitude of little more than 1 km s^{-1} was much smaller than for any star whose orbit had been determined up till that time. Although it was objectively demonstrated that the orbit was very secure, a few years ago subjective misgivings prompted the author to restore the star to his observing programme. New observations of much higher precision confirm not only the spectroscopic-binary nature of 6 Boo but also, with almost astonishing fidelity, the elements already given for it.

Key words. Radial velocities—spectroscopic binaries—orbits—stars: individual—6 Boo.

1. Introduction

This series of papers, which has been in abeyance for the past few years, has given spectroscopic orbits for 34 of the stars discovered (or, in one or two cases, confirmed) to be binaries in the course of the comprehensive survey by Yoss & Griffin (1997) of all the late-type stars that are listed in the *Henry Draper Catalogue* and are within 15° of the North Galactic Pole (NGP). Paper 12 of the series (Griffin 1985) presented the orbit of 6 Boo (HR 5201, HD 120539; also sometimes known as e Boo (Baily 1845; Goldin & Makarov 2007)), a fifth-magnitude K4 III star near the following margin of the NGP field and the ninth-brightest of the stars qualifying for inclusion in the NGP survey.

The observations underlying the orbit in Paper 12 were all made at the Cambridge 36-inch reflector with the original radial-velocity spectrometer (Griffin 1967)—the instrument with which the writer developed the cross-correlation method of measuring radial velocities, which has of course subsequently been universally adopted and has been responsible for most of the evidence for such disparate objects as black holes and extra-solar planets. Although it had been developed as an experimental instrument, it remained in actual research use for 25 years, during which time, of course, it became substantially outmoded. The radial-velocity traces were drawn in real time by a pen on a continuous paper chart, and the reductions were done by measurements made on the chart by hand and eye. Even so, it gave velocities with characteristic errors a little under 1 km s^{-1}, which was regarded as a handsome accuracy at the time that the spectrometer was developed.

The orbit so determined for 6 Boo was the most ambitious one that was ever attempted with the original instrument—it had a velocity amplitude not much more than 1 km s^{-1}, which was about twice the r.m.s. residuals from the orbit. The smallest amplitude found for any plausible spectroscopic orbit previously was 2.39 km s^{-1} (ϕ Her, Aikman 1976). The 6 Boo paper demonstrated how the orbital period, of a little under 1000 days, seemed to be visible in the velocities when they were simply plotted directly against time. Moreover, a statistical argument (kindly vetted by a professional statistician who had been good enough to correct me (Bassett 1978) after I made serious mistakes in the early papers in another series) showed that the orbit was altogether unassailable: a variance-ratio test gave an F ratio of 17.2 in a situation where even the 0.1%-significance level was only 4.9.

All the same, from time to time the writer found himself hoping that the star really does have an orbit much like the one that he asserted for it, and despite the objective evidence that it *does* there came a time when he decided to put it back on his observing programme, which was then being carried out at the same telescope as before but with a spectrometer analogous to the *Coravel* of Baranne *et al.* (1979), which gives velocities of a substantially higher quality than those of the original instrument.

2. Radial-velocity measurements and orbit

There are 35 new *Coravel* observations, made in the years 2004–2009; they are set out in Table 1. An improved scheduling scheme has ensured that they are distributed tolerably uniformly in phase. The earlier paper (Griffin 1985) listed the 54 measurements made with the original radial-velocity instrument and one each with the Palomar (Griffin & Gunn 1974) and Dominion Astrophysical Observatory (DAO; Fletcher 1982) spectrometers. It also listed a few velocities made at Lick (Campbell & Moore 1928) and Mount Wilson (Adams *et al.* 1929; Abt 1973) which were zero-weighted in the solution of the orbit. Since that time one velocity has been published from Ames by Beavers & Eitter (1986), and a listing referred to by de Medeiros & Mayor (1999) has given two more. None of the mentioned measurements has been included in Table 1 other than the 35 new ones obtained at Cambridge; the new orbit presented below utilizes the writer's own earlier data given in Paper 12, but none of the others, which could be considered to be too sparse and too heterogeneous to contribute usefully. It should be explained that the cycle numbers in Table 1 (the numbers before the decimal point in the 'Phase' column) start at the periastron passage preceding the first observation made with the original spectrometer in 1966; although the table gives only the recent *Coravel* measurements, the earlier ones were also used in the computation of the orbit, albeit with low weight.

In the new solution, the Cambridge *Coravel* velocities have been given unit weight, while those made with the original spectrometer have been weighted 1/20, as is needed to bring their weighted variance approximately into line with that of the new observations. The single Palomar and DAO measures have been attributed half-weight. Thus fully 90% of the total weight of the data going into the new orbit is accounted for by the fresh observations, so the result could be considered to all intents and purposes to be an independent orbit. It does, however, benefit by

Table 1. New *Coravel* radial-velocity observations of 6 Boötis.

Date (UT)			MJD	Velocity ($\mathrm{km\ s^{-1}}$)	Phase	$(O-C)$ ($\mathrm{km\ s^{-1}}$)
2004	May	23.00	53148.00	−1.3	14.935	+0.1
	June	25.90	181.90	−1.0	0.970	+0.2
	Aug.	7.86	224.86	−1.2	15.016	+0.1
2005	Jan.	9.25	53379.25	−2.9	15.180	+0.1
	Mar.	25.14	454.14	−3.5	0.259	−0.2
	Apr.	22.06	482.06	−3.3	0.289	+0.1
	May	27.97	517.97	−3.3	0.327	+0.1
	July	9.90	560.90	−3.8	0.372	−0.3
	Aug.	15.87	597.87	−3.7	0.411	−0.2
	Dec.	17.27	721.27	−3.5	0.542	−0.1
2006	Jan.	29.25	53764.25	−3.3	15.588	0.0
	Mar.	1.17	795.17	−3.2	0.620	0.0
	Apr.	4.09	829.09	−3.2	0.656	−0.1
	May	9.97	864.97	−2.9	0.694	+0.1
	June	3.98	889.98	−3.0	0.721	−0.1
	July	2.95	918.95	−2.9	0.752	−0.1
	Aug.	7.87	954.87	−2.6	0.790	−0.1
	Nov.	26.27	54065.27	−1.6	0.907	0.0
2007	Jan.	14.28	54114.28	−1.3	15.958	−0.1
	Feb.	4.21	135.21	−1.5	0.981	−0.3
	Mar.	2.20	161.20	−1.4	16.008	−0.1
	Apr.	1.08	191.08	−1.4	0.040	+0.1
	May	1.04	221.04	−1.9	0.072	0.0
	June	1.03	252.03	−2.4	0.104	−0.1
	July	7.95	288.95	−2.7	0.144	0.0
	Sept.	6.81	349.81	−3.3	0.208	−0.2
2008	Feb.	2.22	54498.22	−3.4	16.365	+0.1
		25.19	521.19	−3.5	0.390	0.0
	Mar.	31.12	556.12	−3.5	0.427	0.0
	Apr.	24.06	580.06	−3.4	0.452	+0.1
		19.02	605.02	−3.4	0.479	+0.1
	June	25.92	642.92	−3.3	0.519	+0.1
2009	Apr.	2.08	54923.08	−2.3	16.816	+0.1
	May	4.03	955.03	−2.1	0.849	0.0
		29.97	980.97	−1.9	0.877	0.0

having its period much improved by the increase of the time base from 5 to 43 years by the inclusion at some level of the writer's older observations; the period obtained from the new data in isolation is 941 ± 7 days. The new solution is plotted in Fig. 1; its elements are given in Table 2, with those determined previously for comparison.

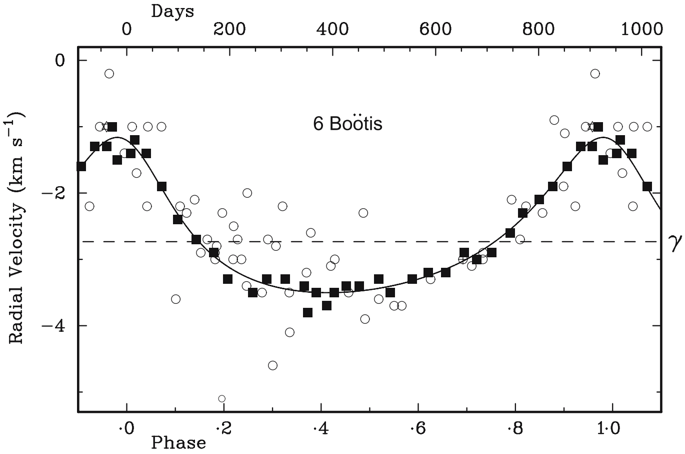

Figure 1. Velocity curve computed from the new orbit for 6 Boötis, with the measured radial velocities plotted. The measurements made with the Cambridge *Coravel* are plotted as filled squares, whereas those made with the original spectrometer (weighted 1/20 in the solution of the orbit) appear as open circles. Single observations from Palomar and the DAO, both weighted 1/2, are shown as a circle with a plus in it, and an open star, respectively.

Table 2. Orbital elements for 6 Boötis.

Element	Griffin (1985)	This paper
P (days)	944 ± 8	943.7 ± 1.1
T (MJD)	44739 ± 31	53210 ± 10
γ (km s^{-1})	−2.63 ± 0.09	−2.734 ± 0.022
K (km s^{-1})	1.19 ± 0.15	1.170 ± 0.031
e	0.41 ± 0.09	0.357 ± 0.025
ω (degrees)	359 ± 15	16 ± 5
$a_1 \sin i$ (Gm)	14.1 ± 1.9	14.2 ± 0.4
$f(m)$ ($M_\odot$)	0.00013 ± 0.00005	0.000128 ± 0.000011
r.m.s. residual (wt. 1) (km s^{-1})	0.6	0.13

3. Discussion

Table 2 and Fig. 1 both demonstrate how very well the old orbit is vindicated by the new one. Arguably the most important elements, P and K, are almost identical in the two solutions. Only two of the seven quantities for which a direct comparison can be made in Table 2, the γ-velocity and ω, differ by more than their joint standard deviation, and then only barely; that is in any case altogether right and proper, since almost one-third of a normal distribution lies outside $\pm 1\sigma$.

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