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THE SPECTROSCOPIC ORBIT OF Π CETI

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ABSTRACT

π Ceti (HR 811, B7 V) has been known to be variable in its radial velocity for almost a century, but its relatively long period and small amplitude have conspired against a determination of its orbit. We have combined in an optimal fashion observations from early in this century with modern measurements to find the spectroscopic orbit with high accuracy. The orbit has a period of 7.45 years and a semiamplitude of 4.3 km/s. The measured eccentricity of $e=0.00\pm0.07$ is indistinguishable from circular, surprising for such a long period. The 76 radial velocity observations available extend over 12 cycles of the orbit. © *1997 American Astronomical Society.* [S0004-6256(97)00303-8]

1. INTRODUCTION

The first observation of the radial velocity of π Ceti (HR 811, B7 V) was made at Lick Observatory with the Mills spectrograph on the 36-inch refractor on 1903 October 20 (Table 1). The variability of its radial velocity was suspected by J. H. Moore after the third plate, taken nearly two years later, showed a significant change in radial velocity. A fourth plate, taken a year after that, confirmed the variability. The variability was announced by Campbell & Albrecht (1909) and by Campbell (1910). The early observations at Lick were published by Campbell (1928), and those of the Yerkes observers by Frost *et al.* (1926), who surmised that the amplitude of variability was probably small.

π Ceti has often been used as a late-B reference star in photometric and spectrophotometric studies (Manfroid *et al.* 1995; Griffin *et al.* 1993; Smith & Dworetsky 1993; Bastiaansen 1992; Roby & Lambert 1990; Cousins 1989; Kilkenny & Menzies 1986). The best determination of its spectral type is that of Garrison & Gray (1994), who have classified it as B7 IV. From high-resolution spectrograms Adelman (1991) confirmed that it is a relatively normal late-B star with mostly near-solar abundances. Its spectrum is relatively narrow lined with a $v \sin i$ value of about 19 km/s (Day & Warner 1975; Hoffleit 1982; Adelman 1991). It is a weak x-ray source (Cash *et al.* 1979; Cash & Snow 1982; Grillo *et al.* 1992).

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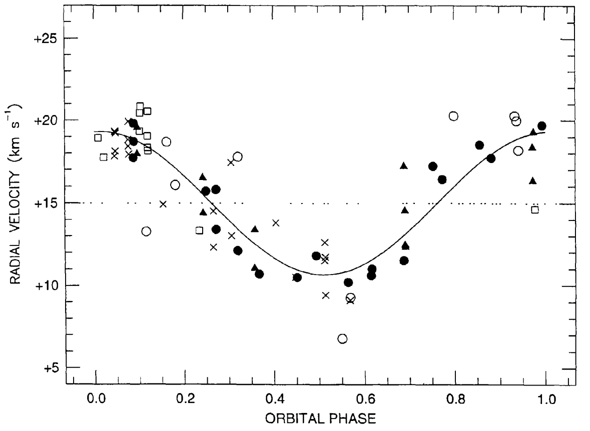

FIG. 1. Radial velocities and fitted orbit of π Ceti. Solid dots are the observations of Fekel; open circles are the observations of Campbell (1928) and Frost *et al.* (1926); crosses are the observations of Lacy; solid triangles are the observations of Mathieu and Morse; open squares are the observations of Morrell and Willmarth.

2. OBSERVATIONS AND ANALYSIS

Our radial velocity observations have been made with a variety of telescopes and coude spectrometers at McDonald Observatory and Kitt Peak National Observatory (KPNO), with a variety of techniques for measuring the velocity and determining the velocity zero point. The spectroscopic resolution was typically 0.03 nm. Photographic spectrograms were obtained by FCF from 1983 to 1985 with the KPNO coudé feed telescope and spectrograph. A mean velocity for each observation was determined by measuring about ten moderate strength lines on a line by line basis in the wavelength region 390 to 455 nm. From 1986 to 1995, FCF obtained TI CCD spectra with the same telescope and spectrometer. The wavelength region between 447.5 and 453 nm was cross correlated with a spectrum of 68 Tau, whose radial velocity of 39.0 km/s was found from cross correlation with 10 Tau (Scarfe *et al.* 1990), an IAU-type velocity standard.

TABLE 1. Observations of the radial velocity of π Ceti.

HJD – 2400000	RV (km/s)	Residuals (km/s)
Observations of Campbell (1928) and Frost et al. (1926)		
16408.88	6.3	-4.1
16457.74	8.8	-1.8
17084.04	19.8	4.0
17448.98	19.8	1.4
17461.00	19.5	1.0
17470.98	17.7	-0.8
17946.69	12.8	-5.0
20793.710	18.2	1.4
20845.553	15.6	-0.7
21227.533	17.3	4.7
Observations of Lacy		
44974.6624	19.7	0.2
44974.6943	18.2	-1.3
44978.5291	19.7	0.2
44978.6423	18.5	-1.0
44980.6424	19.6	0.1
45269.8193	15.3	-2.5
45573.9470	12.7	-2.3
45574.9120	14.9	-0.1
45683.6897	17.8	3.9
45685.7024	13.4	-0.5
45952.9441	14.2	2.4
46070.7158	10.9	-0.4
46245.9884	11.9	0.9
46245.9936	11.9	0.9
46247.9948	13.0	2.0
46249.9929	9.8	-1.3
46249.9984	12.1	1.1
46398.6962	9.5	-1.9
47777.9045	19.2	0.0
47778.9639	18.8	-0.4
47780.0211	20.3	1.1
47782.0259	18.3	-0.9
Observations of Fekel		
45528.991	15.7	0.7
45590.992	15.8	1.4
45591.985	13.4	-1.0
45722.637	12.1	-1.0
46080.588	10.5	-0.4
46386.785	10.2	-0.8
46721.911	11.5	-1.8
47556.655	19.7	0.4
47810.842	17.7	-1.0
47811.780	19.8	1.1
47812.928	18.7	0.0
47813.875	19.8	1.1
48573.782	10.7	-1.4
48916.854	11.8	1.1
49246.960	10.6	-1.1
49251.865	11.0	-0.8
49622.935	17.2	2.2
49677.778	16.4	0.8
49903.982	18.5	0.9
49973.931	17.7	-0.5
Observations of Mathieu and Morse		
46724.86	16.16	3.9
46728.86	13.49	1.2
46730.83	11.41	-1.0
46731.85	11.27	-1.1
47496.67	17.32	-0.9
47499.55	15.29	-2.9
47503.68	18.25	0.0
47832.77	16.92	-0.6
47836.76	18.52	1.0
48232.71	15.47	1.3
48234.65	13.36	-0.8
48546.81	10.02	-1.2
48548.84	12.36	1.1
Observations of Morrell		
47511.7663	14.0	-4.6
47848.8269	18.7	0.9
47849.8232	19.8	2.0
47852.7490	20.2	2.4
47896.7343	17.7	0.2
47897.6830	18.4	0.9
47898.7099	19.9	2.4
47899.6681	17.5	0.0
Observations of Willmarth		
48210.7962	12.7	-2.1
50318.9547	18.3	-0.4
50351.8084	17.1	-1.5

TABLE 2. Orbital elements of π Ceti.

Quantity	Symbol	Value	Standard Error
Orbital period	P (days)	2722	14
Center-of-mass radial velocity	γ (km/s)	+14.98	0.25
Radial velocity semi-amplitude	K (km/s)	4.33	0.25
Eccentricity[a]	e	0.00	...
Julian date of maximum velocity	T_{max}	2444852	29
Projected semi-major axis	$a_1 \sin i$ (AU)	1.08	0.07
Mass function	f(M)	0.023	0.004

[a] When treated as a free parameter, the eccentricity was indistinguishable from zero (0.00 ± 0.07), so it was assumed to be 0 in the final fit.

All of us used some variety of cross-correlation techniques such as FXCOR in IRAF (Lacy 1977; Tonry & Davis 1979; Wyatt 1985) to measure differential velocities, or measured individual line wavelengths. FCF used 68 Tau (HR 1389, A2 IV) as a radial velocity standard, adopting its velocity as 39.0 km/s, putting it on the same scale as that of Scarfe *et al.* (1990). CHSL used *o* Peg (HR 8641, A1 V) as a standard, adopting its velocity as 8.4 km/s, which is consistent with an estimate by Fekel (1990). RDM and JAM used synthetic spectra as standards (Morse *et al.* 1991). The data of NIM and DW obtained at KPNO were reduced together and treated as a single group. Our radial velocities, as well as those of the early investigators, are listed in Table 1. Despite the different measurement techniques and velocity standards that we have used, the velocity offset found for each data set (Table 3) is 1 km/s or less.

In order to fit an optimal orbit from these varied observations, GT developed a new fitting program based on the method of Levenberg–Marquardt (Press *et al.* 1986). It was assumed that each investigator's data set could differ from the others in radial velocity zero point (Δ) and standard error (σ). In this program the weight of each data set depends on its assumed standard error relative to the adopted orbit, so some iteration is required to achieve convergence. The data

TABLE 3. Auxiliary fitting parameters.

Quantity	Data Set of				
	Campbell & Frost et al.	Fekel	Lacy	Mathieu & Morse	Morrell & Willmarth
Offsets Δ (km/s)	+0.5	0	-0.4	+1.0	+0.6
Errors σ (km/s)	3.1	1.1	1.6	1.7	2.1
Observations	10	20	22	13	11

set of FF was chosen to define our radial velocity zero point, and the other Δ's are referenced to his zero point. When treated as a free parameter the orbital eccentricity is determined to be $e=0.00\pm0.07$. Being indistinguishable from circular, we adopted $e=0.0$ for the final orbital solution. The fitted parameters are given in Tables 2 and 3, and the residuals from the final fit are listed in Table 1. The modern observations span about 2 orbital cycles; with the inclusion of the early workers' results, the observations span over 12 cycles, thus substantially improving the accuracy of the orbital period determination.

Combining the small mass function of 0.023 solar masses with a reasonable range of primary masses, it is found that the absorption lines of the secondary will be either always blended with those of the primary or will be too faint to detect. This conclusion is consistent with our lack of detection of a secondary spectrum.

The $v \sin i$ value of π Ceti was determined from a couple of TI CCD spectrograms. For several lines in the 450 nm region the full width at half maximum was measured and an average value found. The instrumental half-width was removed and the resulting mean broadening was calibrated with the results of Gray (1982) and converted into a velocity. We determine a value of 19±1 km/s, in excellent agreement with the results of Day & Warner (1975) and Adelman (1991).

The most surprising and interesting result of our orbital solution is that such a long-period binary has a circular or nearly circular orbit. For a sample of A-type binaries Matthews & Mathieu (1992) found that all systems with periods greater than 10 days had eccentric orbits. Such a period cutoff is similar to that found for late-type dwarfs (Duquennoy *et al.* 1992) and cannot be attributed to tidal circularization in either pre-main-sequence or main-sequence stars. Circularization due to post-main-sequence or main-sequence stars. Circularization due to post-main-sequence evolution, however, remains a possibility. While tides and/or a hydrodynamic mechanism produce circular orbits for evolved systems with periods up to roughly 70 days (e.g., Fekel & Eitter 1989; Boffin *et al.* 1993), giants with much longer periods and nearly circular orbits do exist. Boffin *et al.* (1993) pointed out that a number of normal giants have orbital characteristics similar to Barium stars, whose mean mass function is 0.025 solar masses and mean eccentricity is 0.14. It is currently argued that abundance peculiarities of Barium stars are created by mass transfer from a companion that is now a white dwarf. However, Fekel *et al.* (1993) have shown that the mere existence of a white dwarf companion is not sufficient to produce a Barium star, and Jorissen & Boffin (1992) have argued that an additional parameter is necessary to produce such anomalous-abundance stars. In fact, the π Ceti primary is not known to exhibit anomalous abundances.

π Ceti has a mass function of 0.023 solar masses and a circular or nearly circular orbit, properties consistent with those of known Barium stars. If its B-star primary has a mass of 3 solar masses, its secondary has a likely mass of about 0.7 solar masses, making it a possible white dwarf. While white dwarf secondaries of giant stars have been detected in the ultraviolet (e.g., Fekel *et al.* 1993), the light of the B-star primary would mask a white dwarf in the π Ceti system. Thus, the possibility that π Ceti has a white dwarf secondary and has had its orbit circularized as a result of a mass-transfer event remains a viable scenario.

π Ceti thus joins the ranks of single-lined spectroscopic binaries with accurately determined orbits.

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