THE ASTROPHYSICAL JOURNAL, 396:L91–L94, 1992 September 10

γ CEPHEI: ROTATION OR PLANETARY COMPANION?

GORDON A. H. WALKER,[1] DAVID A. BOHLENDER, AND ANDREW R. WALKER
Geophysics and Astronomy Department, University of British Columbia, Vancouver, BC, Canada V6T 1Z4
AND
ALAN W. IRWIN, STEPHENSON L. S. YANG,[1] AND ANA LARSON
Physics and Astronomy Department, University of Victoria, P.O. Box 3055, Victoria, BC, Canada V8W 3P6
Received 1992 May 19; accepted 1992 June 26

ABSTRACT

In 1988 we reported γ Cep as a single-line, long-period spectroscopic binary with short-term periodic ($P = 2.7$ yr) residuals which might be caused by a Jupiter-mass companion. Eleven years of data now give a 2.52 yr ($K = 27$ m s^{-1}) period and an indeterminate spectroscopic binary period of ≥ 30 yr. While binary motion induced by a Jupiter-mass companion could still explain the periodic residuals, γ Cep is almost certainly a velocity variable yellow giant because both the spectrum and $(R-I)$ color indices are typical of luminosity class III. $T_{\rm eff}$ and the trigonometric parallax give $R_* = 5.8\ R_\odot$ independently. The λ8662 Ca II emission line index varies in phase with the 2.52 yr period which, together with a low $v \sin i$ and the value of R_*, strongly implies that it is in fact the star's period of rotation.

Subject headings: planets and satellites: general — stars: binaries: spectroscopic — stars: chromospheres — stars: rotation — stars: variables: other

1. INTRODUCTION

We (see Campbell & Walker 1979) have developed a technique which measures stellar radial velocities with high precision (PRV) by imposing the *R*-branch of the 3–0 vibration-rotation band of hydrogen fluoride at λ8600 as a wavelength fiducial in the stellar spectra. In 1988 Campbell, Walker, & Yang (1988) published results from the first 6 years of a long-term search for low-mass companions to solar-type stars. The HF technique and analysis are fully described in that paper. They quote a mean external error in an individual radial velocity of 13 m s^{-1} and they applied corrections of the same order to remove systematic differences in zero point between observing runs. Although spectroscopic binaries were deliberately excluded from the sample, two of the 16 stars, γ Cep and χ^1 Ori (see Irwin, Yang, & Walker 1992), proved to be previously undetected single-line spectroscopic binaries, while the remaining program stars showed no variation greater than 50 m s^{-1}, a result which excluded brown dwarf companions in orbits with $P \leq 50$ yr. About half of the stars showed significant variations which could be attributed to the reflex motion from Jupiter-sized planets in orbits of a few AU but much more extensive observations were needed to test this.

In Bohlender et al. (1992) we classify γ Cep (HD 222404) K0 III. In addition to a companion of stellar mass, Campbell et al. (1988) found a 2.7 yr period with an amplitude of 25 m s^{-1} which could be due to a Jupiter-sized companion in a $\sim$2 AU orbit and they cited this as a candidate extra-solar-system planet.

Later we cast doubt on this interpretation (see Irwin et al. 1989 and Walker et al. 1989), when we reported that all five of the yellow giants and the single supergiant, observed in a parallel program as velocity standards, showed significant long-term ($\sim$1 yr) velocity variations. The variations seemed to be intrinsic because the amplitudes were correlated with the level of chromospheric activity for each star. The whole question and interpretation of the yellow giant velocity variability is being actively investigated in a separate program.

With the completion of 11 years of HF PRV observations with the Canada France Hawaii 3.6 m telescope, we are preparing all of the data for 32 dwarf, sub-giant, and giant solar-type stars for publication. However, because of the particular interest raised by a possible planetary companion we examine the data for γ Cep independently in this paper.

2. THE DIFFERENTIAL VELOCITIES AND THE TERNARY ORBIT

Table 1 lists the differential radial velocities of γ Cep by Barycentric Julian Date together with the Ca II line core emission index, $\Delta EW_{\rm Ca\,II}$, based on the equivalent width of the central 1.35 Å of the λ8662 Ca II line relative to 2.27 Å in the adjacent blue wing. Increasing Ca II emission corresponds to increasing $\Delta EW_{\rm Ca\,II}$. The listed changes in effective temperature, ΔT, and $\Delta(R-I)$ have been estimated from several temperature sensitive Fe I and Ti I lines according to the scheme given by Bohlender et al. (1992). No values of $\Delta EW_{\rm Ca\,II}$, ΔT, or $\Delta(R-I)$ are given when contamination by the Solar spectra was suspected. Systematic run corrections have been applied to the data in Table 1. A paper is in preparation describing the technique. It should be emphasised that although the run corrections reduce scatter in the fits to the radial velocities they do not significantly affect the 2.52 yr period discussed below.

The differential velocities for γ Cep are plotted in Figure 1. The solid line is a best fitting ternary orbit in which a sinusoid has been adopted for P_2. The orbital elements are given in Table 2. The 29.9 yr value for P_1 is not a unique solution since arbitrarily longer periods fit equally well. Interestingly, Heintz (1990), from photographic astrometry with the Swathmore refractor, notes a deceleration of the star's proper motion in declination which is compatible with a period of several centuries.

[1] Visiting Astronomer, Canada-France-Hawaii Telescope, operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

TABLE 1

γ Cephei Data

J.D. (−2,440,000)	PRV (m s^{-1})	σ	$\Delta EW_{Ca\,II}$ (mÅ)	σ	ΔT (K)	σ	$\Delta(R-I)$ (m mag)	σ
4754.129	1808.9	15.6						
4771.112	1849.3	23.9	3.31	0.67	−1.6	4.5	−3.3	1.9
4957.885	1689.4	12.2	1.13	0.67	1.9	12.0	−4.6	2.9
5148.078	1572.0	17.8	−0.79	0.56	1.2	4.4	−0.3	2.9
5166.048	1555.3	8.4	−0.73	0.63	3.3	3.6	−6.2	2.3
5212.959	1530.8	13.1	1.44	0.86	3.6	7.5	−4.5	5.8
5276.884	1499.8	8.9	−1.10	0.49	3.4	5.2	−7.5	2.7
5711.703	1280.4	13.7	−0.94	0.47	−6.9	4.4	−4.2	2.8
5712.786	1258.4	11.0	1.88	0.51	−3.7	2.8	−0.1	0.8
5811.130	1211.1	9.7	−1.54	0.47	−2.6	3.4	−3.7	2.4
5865.136	1166.4	12.6						
5902.042	1103.7	9.1	−1.16	0.48	−2.4	2.1	−0.4	2.2
6047.771	1006.0	9.7	−1.11	0.41	2.0	3.3	−4.1	1.5
6047.783	992.5	10.8	−1.25	0.41	0.3	2.5	−2.4	1.0
6217.144	856.4	14.7						
6284.004	801.7	22.4	−2.14	0.48	−2.5	2.5	1.9	1.2
6284.010	801.7	15.5	−1.29	0.58	−3.7	3.7	1.0	1.0
6393.804	719.0	15.1	0.37	0.38	−1.9	5.5	3.0	4.5
6394.858	740.9	12.7	−0.78	0.44	−3.1	3.0	4.8	1.5
6605.100	550.2	9.3	0.71	0.53	2.3	3.7	−2.9	3.3
6725.830	449.6	6.0	−1.10	0.43	1.4	4.0	−2.4	5.2
6726.857	453.8	8.7	0.17	0.49	−3.3	5.7	−9.4	4.8
6784.821	399.0	7.2	1.54	0.55	2.9	6.2	−14.1	5.6
6785.844	390.2	10.0	−0.41	0.49	7.7	8.7	−4.6	2.1
6834.758	341.9	10.6	−0.59	0.70	0.3	2.7	−0.7	1.3
6865.700	343.9	8.6						
6961.130	208.4	8.1						
6962.110	188.2	7.6	0.59	0.53	1.8	2.9	−5.2	2.8
7020.074	113.6	8.1	−0.67	0.46	−2.6	4.5	−2.7	5.2
7021.064	118.1	8.3	−0.81	0.49	−7.8	4.4	−2.4	2.6
7101.941	46.2	7.2	−1.54	0.46	2.4	5.3	−2.9	1.6
7101.949	49.9	6.4	0.04	0.43	3.0	3.2	−1.3	1.4
7102.946	53.8	6.3	−1.38	0.47	−0.7	8.1	0.0	1.9
7102.955	59.4	6.9	−1.91	0.50	−4.4	9.4	1.8	2.2
7160.823	−1.5	13.0	−1.90	0.63	5.6	7.3	−3.2	2.3
7307.110	−144.1	8.2	0.11	0.48	−11.1	6.6	0.2	2.8
7307.118	−120.4	8.5	−0.04	0.51	−8.8	5.3	−1.2	2.3
7308.109	−124.5	12.2	−0.40	0.53	−0.4	5.1	1.5	1.3
7339.040	−148.3	8.5	0.70	0.50	1.8	4.8	−5.7	7.2
7339.054	−178.3	9.9	0.74	0.52	6.2	8.1	−11.2	4.4
7340.026	−165.3	8.0	0.47	0.54	4.1	4.1	−2.8	6.3
7370.988	−195.0	10.6	0.66	0.57	−2.4	4.0	−4.0	2.0
7371.997	−199.2	10.3	1.44	0.57	−2.4	4.6	−2.1	1.8
7372.000	−207.2	10.9	1.26	0.59	−6.1	3.9	−1.4	1.5
7454.836	−253.3	7.9	1.11	0.69	−0.8	4.9	−2.9	4.8
7519.833	−291.5	11.5	3.29	0.53	3.8	2.3	2.0	1.4
7545.691	−311.8	13.4						
7636.132	−388.6	14.3	0.73	0.46	−0.6	3.5	2.3	1.1
7636.137	−400.6	12.4	1.42	0.53	3.8	3.3	1.0	1.1
7637.090	−387.9	13.8	0.35	0.50	−1.4	3.6	9.8	2.8
7699.114	−470.8	13.0	1.78	0.60	−1.5	5.3	−2.4	2.0
7700.113	−495.5	18.3	−0.23	0.77	1.6	3.9	−0.1	1.0
7700.124	−489.9	13.7						
7788.033	−585.1	8.1	0.04	0.43	−4.7	3.2	9.6	2.4
7788.927	−583.8	7.7	−0.17	0.43	−5.4	5.8	−0.4	6.4
7788.932	−582.1	7.1	−0.32	0.42	−3.9	5.9	−0.6	5.4
7894.820	−676.1	17.0	−0.71	0.63	−0.6	3.6	0.6	1.0
8112.988	−858.2	7.6	−0.03	0.49	−4.5	3.2	4.4	1.0
8112.993	−864.1	7.2	0.14	0.62	−3.7	4.0	3.0	0.9
8113.997	−873.1	5.8	−0.78	0.47	−0.6	3.3	0.9	0.8
8290.776	−948.8	18.2	−4.32	1.53	1.6	4.5	−2.8	2.0
8406.104	−957.0	17.5	1.19	0.62	11.9	11.6	14.5	5.7
8406.111	−966.0	17.9	1.38	0.57	10.3	10.0	12.0	4.8
8407.107	−982.2	10.4	0.87	0.63	0.6	4.2	0.2	1.1
8471.021	−1025.7	8.6	−0.40	0.48	0.8	3.6	−1.4	1.4
8471.976	−972.5	12.1	0.05	0.63	4.7	2.4	−1.1	1.0
8577.852	−1062.6	6.7	0.13	0.58	−0.3	4.3	7.8	2.7
8578.810	−1044.6	7.4	−0.78	0.52	−0.6	5.0	9.1	3.1
8578.819	−1048.6	9.0	−0.92	0.59	−4.3	5.4	7.8	2.1

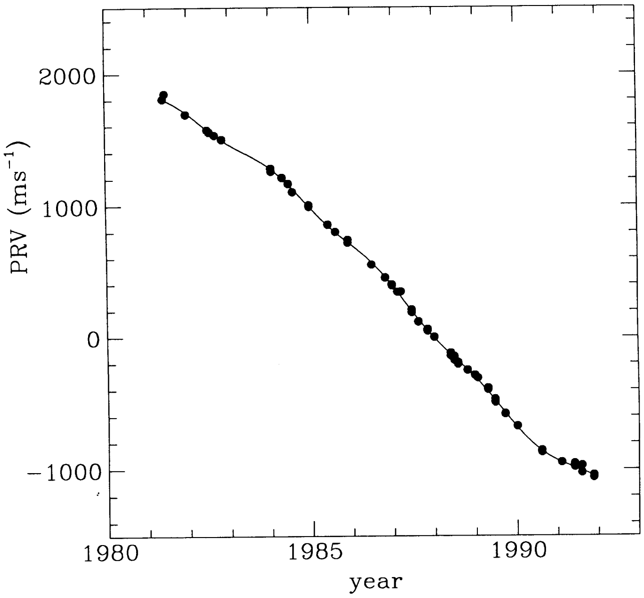

FIG. 1.—Differential radial velocities of γ Cep measured by the HF technique. The solid line is a best fitting ternary orbit with 29.9 and 2.52 yr periods.

For the purposes of this paper, the elements of P_2 are unaffected by the particular choice for P_1.

Figure 2 shows the velocity residuals from the 29.9 yr orbit phased to $P_2 = 2.52$ yr. The significance of the sinusoid fit is at the 11 σ level in the K amplitude.

3. LUMINOSITY, YELLOW GIANT VARIABILITY, ROTATION

In Bohlender et al. (1992) we demonstrate that, spectroscopically, γ Cep is more typical of luminosity class III than IV. Heintz (1990) gives a trigonometric parallax of 0".061 from which we derive $R_* = 5.8\ R_\odot$ using $T_{\rm eff} = 4904$ K from Bell & Gustafsson (1989). While 5.8 $R_\odot$ is small, it is just compatible with luminosity class III which is compatible with the classification as K1 III–IV CN 1 by Keenan & McNeil (1989).

γ Cep displays quite weak chromospheric activity. Wilson (as reported by Zirin 1976) gives the values of 1 and 65 km s^{-1} for the intensity and width, respectively, of the Ca K line. These levels are lower than for any of the giants except β Gem in the Walker et al. (1989) paper. The λ10830 He line is also very weak (Zirin 1976).

In Walker et al. (1989) we have shown that there is a direct correlation between the level of chromospheric activity and the degree of radial velocity variability for the yellow giants. γ Cep conforms to this pattern. After removing P_1 from the data we find $\sigma_v = 25$ m s^{-1} (15 m s^{-1} with P_2 removed). This value of σ_v combined with the width and intensity values from Wilson are very similar to those for β Gem which basically delineates the zero point of the correlation.

More important than the degree of activity is the significant periodicity close to P_2 in $\Delta EW_{\rm Ca\,II}$. An independent sinusoidal best fitting period of 2.48 yr for $\Delta EW_{\rm Ca\,II}$ is given in Table 2 and the data are plotted, folded on this period in Figure 3. The fit is significant at the 5 σ level in the $\Delta EW_{\rm Ca\,II}$ amplitude and, over the 4.4 cycles of the data, it does not differ significantly in phase from P_2.

A magnetic cycle as short as 2.48 yr is most improbable for a star of this size. The Ca II modulation is much more likely to be caused by rotation. From $R_* = 5.8\ R_\odot$ we predict a maximum value of $v \sin i \sim 0.3$ km s^{-1}. While we cannot resolve this level of line broadening in our spectra, we note that Gray & Nagar (1985) set limits to $v \sin i$ for γ Cep of 0 to 0.8 km s^{-1}, entirely consistent with our result.

We find no related periodicity in the values of ΔT or $\Delta(R-I)$ in Table 1. In fact, $T_{\rm eff}$ has not changed by more than 10 K throughout the 11 years of observations. Given the subtlety of change in the chromospheric and apparently related radial velocity variations, the negative result for $T_{\rm eff}$ is not unexpected.

4. PLANETARY COMPANION OR VELOCITY VARIABLE STAR?

Formally, an explanation of $P_2 = 2.52$ yr in terms of the reflex motion about a Jupiter-mass planet in a highly circular orbit with $M \sin i = 1.3 \times 10^{-3}\ M_\odot$ is still viable but, to survive so close to a stellar K giant, the planet would need to be solid. A Jupiter mass of solid material would greatly exceed

TABLE 2

PERIODIC SOLUTIONS FOR γ CEPHEI

Parameter	Value
Radial Velocities	
γ (ms^{-1})	878.5 ± 400
K_1 (ms^{-1})	1645.2 ± 200
e	0.20986 ± 0.081
ω	−164°15 ± 33°0
T_1 (days)	9093 ± 500
P_1 (days)	10963 ± 4600
K_2 (ms^{-1})	26.852 ± 2.5
T_2 (days)	7579.3 ± 16.0
P_2 (days)	922.56 ± 20.0
$\Delta EW_{\rm Ca\,II} = \gamma + K \cos[2\pi(t-T)P^{-1}]$	
γ (mÅ)	−0.13 ± 0.12
K (mÅ)	0.92 ± 0.18
T (days)	7495 ± 28
P (days)	906 ± 29

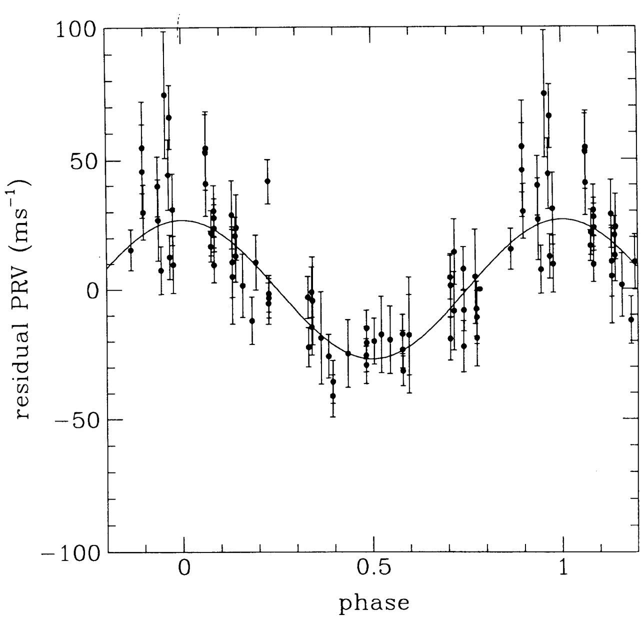

FIG. 2.—Velocities from Table 1 folded on the 2.52 yr period after removing the 29.9 yr period.

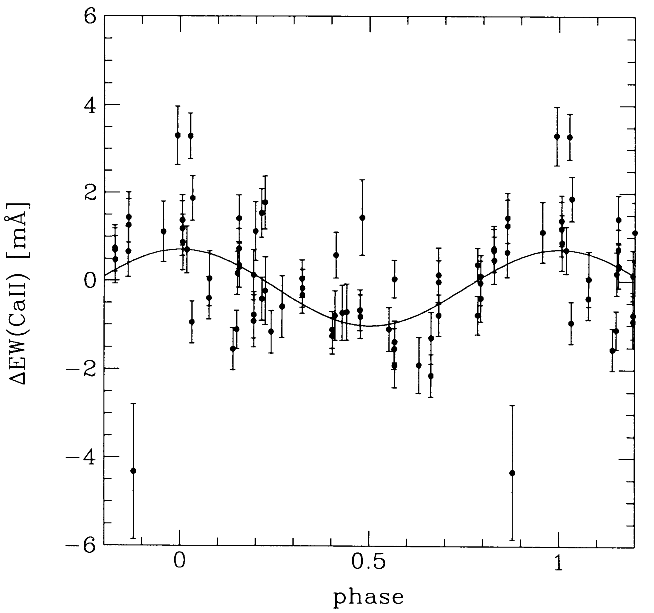

FIG. 3.—Variation of the central 1.35 Å of the λ8662 Ca II line (see text) folded on a best-fitting 2.48 yr sinusoidal period.

the combined masses of the terrestrial planets and the cores of the solar system gas giants.

Rotational modulation of an azimuthal photospheric velocity structure and related chromospheric activity seems much more plausible. If the chromospheric activity is associated with active regions on the surface, then one might expect photospheric velocities or convection velocities to be sympathetically modified. Uneven weighting of the integrated velocity across the visible disk due to spots could also contribute to the effect. Alternatively, the azimuthal dependence of the photospheric velocities might even be associated with giant convective cells, or *g*-mode subharmonic oscillations.

It is worth noting that several other yellow giants show periodicity in their long-term radial velocity variations, e.g., Arcturus (Irwin et al. 1989), γ^2 Del (1992, in preparation), β Gem (McMillan 1992), and HR 152 (McClure et al. 1985). Whether any of these periodicities can be tied to rotation has yet to be demonstrated.

Unlike the giants, rotation of Solar-type dwarfs is unlikely to lead to long-period velocity variations which mimic perturbations by Jupiter-mass companions in short-period orbits. Rotation periods for the dwarfs are more typically months rather than years. For this reason we do not expect the same ambiguity of interpretation in our dwarf PRV program.

This research was supported by funds from the Natural Sciences and Engineering Research Council of Canada. Jaymie Matthews made very helpful comments on this paper in manuscript, and it is a pleasure to acknowledge the many observations contributed by Bruce Campbell and more recently the observing assistance of John Glaspey.

REFERENCES

Bohlender, D. A., Irwin, A. W., Yang, S., & Walker, G. A. H. 1992, PASP, submitted
Campbell, B., & Walker, G. A. H. 1979, PASP, 91, 540
Campbell, B., Walker, G. A. H., & Yang, S. 1988, ApJ, 331, 902
Gray, D. F., & Nagar, P. 1985, ApJ, 298, 756
Heintz, W. D. 1990, AJ, 99, 420
Irwin, A. W., Campbell, B., Morbey, C. L., Walker, G. A. H., & Yang, S. 1989, PASP, 101, 147
Irwin, A. W., Yang, S., & Walker, G. A. H. 1992, PASP, 104, 101
Keenan, P. C., & McNeil, R. C. 1989, ApJS, 71, 245
McClure, R. D., Griffin, R. F., Fletcher, J. M., Harris, H. C., & Mayor, M. 1985, PASP, 97, 740
McMillan, R. S. 1992, private communication
Walker, G. A. H., Yang, S., Campbell, B., & Irwin, A. W. 1989, ApJ, 343, L21
Zirin, H. 1976, ApJ, 208, 414