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COMMENTS ON THE VARIABILITY AND PHYSICAL PARAMETERS OF THE F SUPERGIANT PHI CASSIOPEIAE

A. ARELLANO FERRO*†‡

Instituto Nacional de Astrofísica, Optica y Electrónica
Ap. Postal 51 y 216, Puebla 72000, México

L. PARRAO

Instituto de Astronomía, Universidad Nacional Autónoma de México
México D.F., 04510, México

AND

SUNETRA GIRIDHAR

Indian Institute of Astrophysics, Bangalore 560034, India

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ABSTRACT

UBVRI and *uvby* photometry and radial velocities have been obtained for the F0 I*a* supergiant ϕ Cas. The variability is confirmed from the radial velocities; the velocity range is small ($\Delta V_r \sim 6$ km sec^{-1}). No indication is found of strict periods longer than 15 days. The physical parameters T_e = 7300 K $\pm$ 300 K, $R = 245 \pm 45\, R_\odot$, $\mathfrak{M} = 17 \pm 3\, \mathfrak{M}_\odot$, and $\log g = 0.9 \pm 0.2$ are estimated.

Key words: supergiant star–possible variability–photometry–radial velocities

I. Introduction

The yellow supergiant ϕ Cassiopeiae (F0 I*a*) is one of the brightest stars in our Galaxy; it has $M_v \sim -8.4$ and together with the well-known variables HR 8752 ($M_v \sim -9.1$), ρ Cassiopeiae ($M_v \sim -9.5$), and ϵ Aurigae ($M_v \sim -8.7$) it might be classified as a hypergiant star. Generally F–G supergiant stars have been found to be variable in either light, radial velocity, or both; however, the variability of ϕ Cas has not been solidly established, mainly due to the lack of the systematic long-term monitoring of light or radial velocity as well as the apparent small amplitude and probable long period of the variation.

Among the galactic long-period ($P > 40$ days) variables in the yellow supergiant region of the H-R diagram, there are stars with a variety of physical properties. One finds the "normal" massive and luminous stars like HR 8752 (G0 I*a*), ρ Cas (F8 I*a*p), or ϵ Aur (F0 I*a*) (Arellano Ferro 1985), and also the controversial high-galactic-latitude stars like 89 Herculis (F2 I*a*), HD 161796 (F3 I*b*), HR 4912 (F3 I*a*), or HR 7671 (F2p), some of which have been suspected of being low mass ($\mathfrak{M} \sim 1\, \mathfrak{M}_\odot$) stars from the old-disk population mysteriously masked as young massive supergiants (Fernie and Garrison 1984; Luck, Lambert, and Bond 1983).

ϕ Cas has long been neglected by the observers, perhaps because there have been no arguments to suspect it of being a peculiar star. For this reason we consider it of importance to discuss its variability and physical parameters as implied by recent *UBVRI* and *uvby*β photometry and radial velocities. In the following sections we undertake such a discussion.

II. Observations

A. *UBVRI Photometry*

ϕ Cas was observed differentially relative to the stars HR 326 (B8 V) and HR 439 (K0 I*b* + B9 V), called C1 and C2, respectively, from 1981 September 11 to 26 with the No. 4 0.4-m telescope at Kitt Peak National Observatory and on October 8 with the 0.6-m telescope at David Dunlap Observatory. The comparison stars were selected after Percy and Welch (1981). The observations were reduced to the standard system through the observations of standard stars taken from Iriarte *et al.* (1965). The reduction process has been described in detail by Arellano Ferro (1984). The data are listed in Table I.

B. *Radial Velocities*

The radial velocities were measured from 1980 October 8 to 1981 November 18 with the 1.88-m telescope at David Dunlap Observatory and from 1981 August 12 to August 17 with the 1.83-m telescope at Dominion Astro-

*On leave from Instituto de Astronomía, UNAM.

†Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

‡Visiting Astronomer, Dominion Astrophysical Observatory.

TABLE I

UBVRI PHOTOMETRY OF φ CAS

V	U-V	B-V	V-R	V-I	HJD(244 0000.+)	notes
4.965	1.181	0.694	0.638	1.114	4861.9473	KP
4.958	1.173	0.682	0.650	1.122	4862.9565	KP
4.955	1.199	0.688	0.618	1.142	4863.8979	KP
4.949	1.195	0.684	0.631	1.082	4864.8872	KP
4.949	1.184	0.679	0.636	1.121	4867.9478	KP
4.953	1.178	0.686	0.631	1.074	4868.8916	KP
4.960	1.180	0.691	0.625	1.127	4871.9292	KP
4.958	1.197	0.692	0.641	1.138	4872.9131	KP
4.948	1.203	0.691	0.632	1.127	4873.8589	KP
4.954	1.201	0.684	0.685	1.087	4874.8804	KP
4.930	0.985	0.729	0.633	1.122	4886.8096	DDO

physical Observatory. The observational material and reduction techniques have been described by Arellano Ferro (1984). The radial velocities are listed in Table II.

C. *uvbyβ Photometry*

These data were obtained from 1986 October 19 to 23, with a four-channel spectrograph photometer having spectral passbands with central wavelengths and widths close to those of the standard *uvby*β filters. The pulse-counting photometer is equipped with uncooled EMI 9789QA photomultipliers. This instrument was attached to the 1.5-m telescope at San Pedro Martir Observatory (Mexico).

φ Cas was observed together with a large group of bright F-type supergiants selected from the *Bright Star Catalog* (Hoffleit 1982), which are part of a different program. All observations were reduced to the Crawford system by means of standard stars from Crawford and Barnes (1970). Table III gives the individual observations of φ Cas. The uncertainties of each individual observation are estimated to be 0.010, 0.004, 0.006, and 0.015 in V, $(b-y)$, m_1, and c_1, respectively.

III. Variability

The variability of φ Cas has been suspected in the past but never solidly established: Abt (1957) found an increase of ~ 4 km s^{-1} in two weeks and quotes Adams, Joy, and Sanford (1924) as discoverers of the variability; however, we failed to find φ Cas in the tables of Adams *et al.*'s paper. Percy and Welch (1981) reported a scatter in V of 0.02 mag from four observations gathered within 28 days. Although the variability might be real and a small amplitude and long period cannot be excluded, nothing is really

TABLE II

RADIAL VELOCITIES OF φ CAS

V_r (Km/s)	σ(Km/s)	HJD (2410000.+)	Plate No.	Notes
-28.54	0.56	4521.814	45121	DDO
-29.39	0.70	4548.830	45191	DDO
-26.19	0.55	4549.709	45204	DDO
-31.25	0.75	4569.682	45274	DDO
-25.80	1.75	4670.586	45555	DDO (weak)
-24.69	0.63	4672.665	45556	DDO
-24.61	0.62	4684.524	45595	DDO
-27.86	0.74	4710.549	45705	DDO
-23.92	0.65	4746.854	45854	DDO
-27.92	0.87	4768.799	45915	DDO
-27.40	0.54	4822.800	46070	DDO
-27.10	0.76	4829.950	88805	DAO
-28.03	0.69	4832.990	88842	DAO
-27.89	0.50	4833.950	88855	DAO
-27.43	0.51	4834.933	88871	DAO
-25.73	0.40	5292.684	47265	DDO

TABLE III

uvbyβ PHOTOMETRY OF φ CAS

J.D.	V	(b-y)	m1	c1	β
244 6722.797	4.973	0.480	0.030	1.423	2.651
244 6723.815	4.978	0.486	0.020	1.434	2.646
244 6726.846	4.989	0.481	0.041	1.396	2.647

known about the nature of the variability of φ Cas. To our knowledge the most recent available data are those described in the previous section and we have used them to search for any variability and periodicity. In Figure 1 we have plotted the differential values $P-C1$, $P-C2$, and $C1-C2$ for the magnitude V and the color index $(B-V)$. Note that on Figure 1 only data from Kitt Peak have been plotted; thus, differences between photometric systems cannot be invoked. Scatter with amplitudes between 0.01 and 0.06 mag is displayed. However, the differential values for the comparison stars, HR 326(C1) – HR 439 (C2), are comparable to the values $P-C1$ and $P-C2$; hence, variability cannot be claimed from these observations.

The radial-velocity measurements in Table II are plotted in Figure 2; they span slightly over a year and the range is about 6 km sec^{-1}. Since the internal accuracy is better than 1 km sec^{-1}, the variations are probably real. We have carried out a Fourier analysis for unequally spaced data using the algorithms of Deeming (1975) and Scargle (1982) on these radial velocities and find no peaks in the power spectrum for periods longer than 15 days. Prominent peaks occur between 10–15 days and between 1 and 2 days, the latter being probably due to the one-day observing window. Scargle's algorithm allows us to calculate the level of significance for a given peak in the power spectrum. According to this all of the more prominent peaks have a significance of less than 10%. Hence we do not want to put much emphasis on the periodicity of φ Cas since evidently the data we have on hand are not adequate for the proper period analysis. The photometry is dense, but it only spans 15 days, and the radial velocities span about one year, but are scarce. Thus, an irregular variation with a characteristic time of weeks or months cannot be ruled out. However, we want to emphasize that data recently obtained (Fig. 2) clearly show variations of low amplitude ($\Delta V_r \sim 6$ km sec^{-1}). A more-detailed monitoring is necessary to establish whether or not these variations are periodic.

IV. Physical Parameters

Important information on the physical parameters of φ Cas can be derived from the *uvby* photometry in Table III. Since the variability of φ Cas is of very small amplitude, we have used the average of the color indices given in Table IV.

Assuming that φ Cas is a member of NGC 457 (Pesch 1959; Humphreys 1978), its color excess must be that of the cluster, $E(B-V) = 0.50$ (Pesch 1959), $E(B-V) = 0.49$ (Mermilliod 1981), or $E(B-V) = 0.47$ (Nicolet 1981). A spectral type, color relationship (Schmidt-Kaler 1982) and functional formula for $E(B-V)$ in terms of $(B-V)$ and $(R-I)$ (Fernie 1982) give $E(B-V) = 0.52$ and $E(B-V) = 0.24$, respectively. We have adopted $E(B-V) = 0.49$. Thus

$$E(b-y) = 0.73 \times E(B-V) = 0.36$$

(Crawford 1975), which agrees well with $E(b-y) = 0.382$ found by Eggen (1982) from *uvby* photometry. The dereddened colors are given in Table IV.

The mean color index $(b-y)_0 = 0.124$ is consistent with the F0 spectral type, although a comparison of our mean value Hβ = 2.648 with the Hβ-spectral type relationship for F-type stars (Crawford and Mander 1966); Crawford and Perry 1976) predicts a spectral type of F6–F7; however, φ Cas is an MK standard for F0 I*a* type. A similar inconsistency was found by Fernie (1986*a*) for the peculiar F2p supergiant HR 7671 in both Hβ and $(b-y)_0$. Such an inconsistency does not exist, for example, in the F-type supergiants 89 Herculis (β = 2.67, Fernie 1986*b*) and HD 161796 (β = 2.69, Fernie 1986*b*).

Figure 3 shows a plot of $(b-y)_0$ versus $(m_1)_0$. The positions of φ Cas and the bright F-type supergiants selected from the *Bright Star Catalog* and also observed are shown relative to the atmospheric models (Kurucz 1979) for three values of [Fe/H] and $\log g = 2$. This clearly shows that φ Cas, as expected, has solar abundance. For $\log g = 1$ the models would have to be shifted by about 0.02 toward higher values of $(m_1)_0$ and would not change the above conclusion.

Figure 4 is a plot of $(b-y)_0$ versus $(c_1)_0$. This diagram is sensitive to $\log g$ and T_e. Solid curves are atmospheric models (Kurucz 1979) for several values of $\log g$ and T_e and for [Fe/H] = 0. φ Cas and the group of bright F supergiants are also plotted. φ Cas appears as having $\log g \sim 2$ and $T_e \sim 7300$. Uncertainties in the reddening will

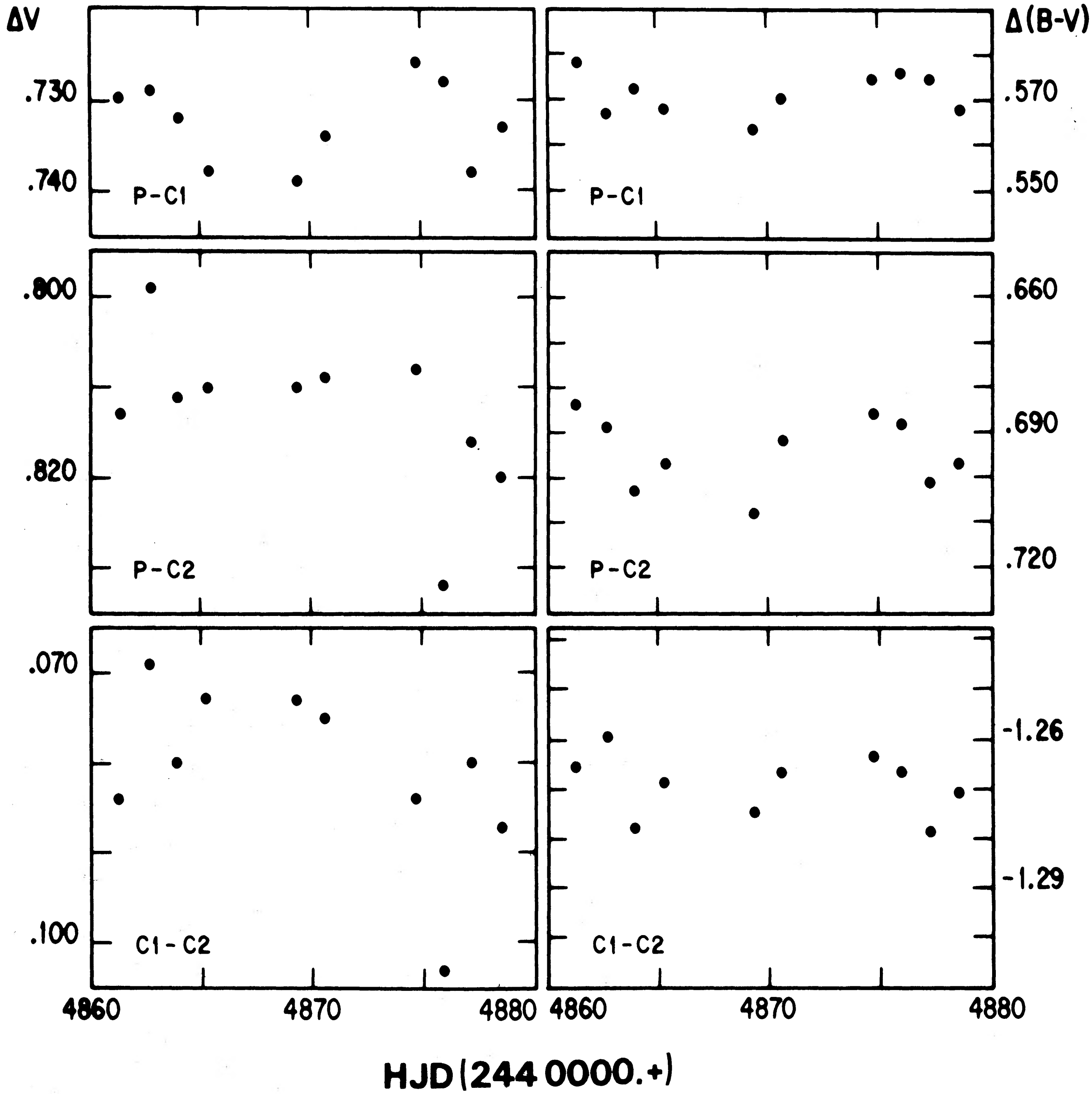

FIG. 1–Differential photometry of ϕ Cas (P) relative to HR 326 (C1) and HR 439 (C2) in V and $(B-V)$.

move the star horizontally on Figure 2. The dispersion of values of $E(B-V)$ discussed above would change log g by about 0.5 and T_e by about 300 K. However, the theoretical models are probably too sparse and uncertain to offer a firm value of log g. The two F supergiants below log $g = 3$ are HR 1125 (F5 II) and HR 8718 (F5 II). These are part of a different spectroscopic and photometric program and shall be discussed in a separate paper.

A recent calibration of M_v as a function of $[m_1] = m_1 + 0.32\,(b-y)$ and $[c_1] = c_1 - 0.20\,(b-y)$ valid for F supergiants has been derived by Antonello (1985). Such calibration predicts $M_v = -7.9 \pm 0.54$ which has to be compared with -8.8 (Pesch 1959), -8.5 (Humphreys 1978), -8.7 (Mermilliod 1981), and -7.9 (Eggen 1982) all of which assume the membership of ϕ Cas in NGC 457. Adopting $M_v = -8.4 \pm 0.4$ and $T_e = 7300$ we find a radius $R = 245 \pm 45\ R$ and, comparing it with Iben's (1967) evolutionary tracks, a mass $\mathfrak{M} = \sim 17 \pm 3\ \mathfrak{M}_\odot$ can be predicted for ϕ Cas. These values for mass and radius imply log $g = 0.9 \pm 0.2$.

Except for the mass, the above results are in reasonable concordance with the values derived from an atmospheric model for ϕ Cas recently calculated by Rosenzweig (1987); $\log g = 0.4 \pm 0.1$, $T_e = 7200$ K $\pm$ 100 K, $\mathfrak{M} = 6.3 \pm 3.6\,\mathfrak{M}_\odot$, and $R = 263 \pm 34\,R$.

There is a large inconsistency in the value of $\log g$ as obtained from M_v (0.9 $\pm$ 0.1) or from Rosenzweig's atmospheric model (0.4 $\pm$ 0.1) and that obtained from *uvby* data and Kurucz's models (2.0 $\pm$ 0.5). Unfortunately Kurucz's models do not cover $\log g < 1$ and may not be fully applicable to very low-gravity stars. Models specially developed for very low gravities are needed. Therefore, $\log g \sim 2.0$ is likely to be too large for ϕ Cas.

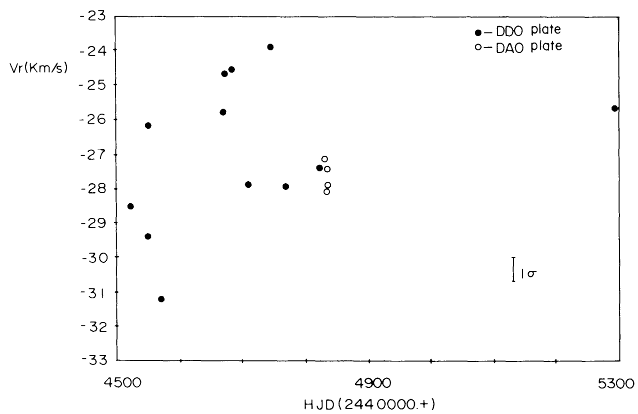

FIG. 2–Radial-velocity variations of ϕ Cas.

V. Conclusions

We have presented evidence of very small amplitude ($\Delta V_r \sim 6$ km sec^{-1}) variability in the F supergiant ϕ Cas, although nothing can really be said at present on the nature of such variations. Due to the scarcity of data, the periodicity cannot be assessed but no indication was found of variations on time scales longer than 15 days.

Measurements in the *uvby* system indicate ϕ Cas to be a normal Population I yellow supergiant, i.e., solar abundance, $\log g = 0.9 \pm 0.2$, $T_e = 7300$ K $\pm$ 300 K, $R = 245 \pm 45\,R_\odot$, and $\mathfrak{M} = 17 \pm 3\,\mathfrak{M}_\odot$. If the evolutionary models of Maeder (1980) are adopted, ϕ Cas has evolved from a very massive ($40 < \mathfrak{M}/\mathfrak{M} < 60$) main-sequence star. The above parameters make ϕ Cas of the same kind as the hypergiants HR 8752, ρ Cas, and ϵ Aur, which show nonradial pulsations (Arellano Ferro 1985). If ϕ Cas were pulsating in a nonradial way, a Q value larger than 0.06 would be expected (Arellano Ferro 1985). Thus, given the determined mass, luminosity, and temperature, a period of about 70 days would be required. The observations on hand do not seem to indicate such a large period, but they are scarce. A long-term and more dense observational

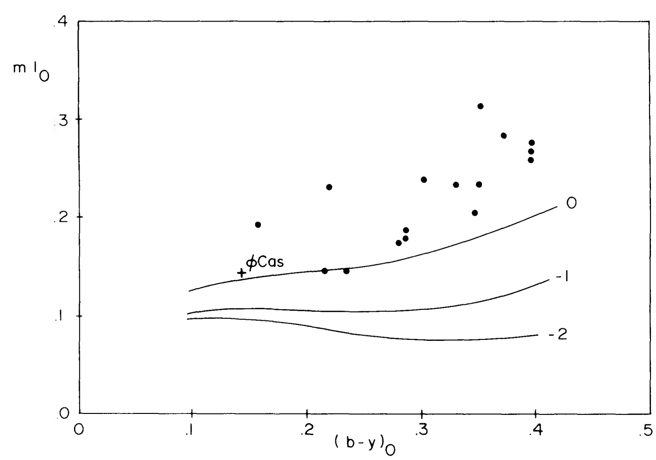

FIG. 3–This diagram is sensitive to atmospheric metal abundance. Dots represent Population I bright F supergiants. Solid curves are three atmospheric models (Kurucz 1979) for [Fe/H] = 0, -1, and -2; all three are for $\log g = 2$. The position of ϕ Cas is indicated by a cross.

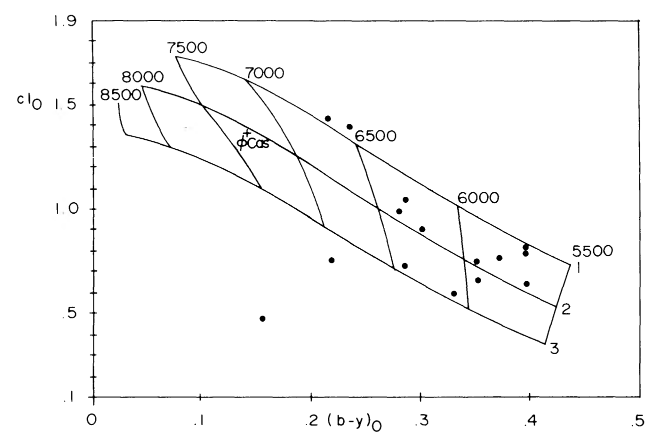

FIG. 4–This diagram is sensitive to temperature and gravity. Solid curves represent theoretical models (Kurucz 1979), for a set of temperatures, 5000 K to 8500 K, and gravities, $\log g$ = 1, 2, and 3, all for [Fe/H] = 0. Symbols are as in Figure 2.

TABLE IV

MEAN PHOTOMETRIC INDICES OF ϕ CAS

V V_o	(b-y) $(b-y)_o$	m1 $m1_o$	c1 $c1_o$	β
4.98	0.482	0.030	1.418	2.648
3.51	0.124	0.144	1.346	

project on the light and radial-velocity variations of ϕ Cas will surely be rewarded by a better understanding of the pulsational nature of this bright supergiant.

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