PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 112:642–647, 2000 May

V529 Coronae Austrinae: An RV Tauri Variable of Type RVb[1]

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Received 1998 January 5; accepted 2000 February 20

ABSTRACT. We present an analysis of the photometric data on V529 CrA. The data include published photographic data as well as our own $UBV(RI)_C$ measurements. Two dominant modulations with periods of 23.571 and 761.5 days are present in the light curve. The double of the 23.571 day period (47.142 days) shows the alternating deep/shallow minima behavior of the RV Tauri class of variables, while the presence of a longer modulation indicates a classification in the photometric subclass RVb. Medium-resolution optical spectroscopy is also presented.

1. INTRODUCTION

The RV Tauri stars belong to a small group of luminous, pulsating variables, identified photometrically by the presence of alternating deep and shallow minima in their light curves. The period between adjacent deep minima (called the formal period) ranges from 30 to 150 days. Spectroscopically they show spectral types in the range F–K, with luminosity class Ia–II. In addition, such variables are subdivided in two photometric subclasses, RVa and RVb (Kholopov et al. 1985), and three spectroscopic types, A, B, and C (Preston et al. 1963). The stars classified as RVa present constant mean brightness, while the objects of the RVb subgroup show, besides the more rapid variations, a long-term modulation of 600–2500 days. The spectroscopic types are defined as follows: (1) In type-A objects all the spectral features indicate G or K spectral types, although TiO absorption bands have been detected in some objects near primary minimum indicative of M spectral type. (2) The type-B objects show peculiar F spectra near maximum light. They show weak metal-line absorption and enhanced carbon abundance. (3) The C-type objects are also weak-lined stars, but the CH and CN bands are weak or absent. The RV Tauri variables found in globular clusters belong to this latter group. Recent studies on RV Tauri stars can be found in Pollard et al. (1996, 1997; photometry and spectroscopy) and in Gonzalez, Lambert, & Giridhar (1997, and references therein; abundance analysis).

In this paper we present the results of an analysis of the available photometric data on V529 CrA, an object listed as type I in the fourth edition of the *General Catalogue of Variable Stars* (Kholopov et al. 1985); i.e., it is an irregular variable with unknown features of light variation and spectral type. The present analysis has been carried out in the course of a photometric and spectroscopic program on southern and equatorial irregular variables. One of the goals of this program was to discover objects like cataclysmic variables, symbiotic stars, and other types of peculiar objects among them, as well as to collect data to better classify and understand such variables. The results of this survey can be found in Cieslinski, Jablonski, & Steiner (1997) and Cieslinski, Steiner, & Jablonski (1998).

2. OBSERVATIONAL DATA

2.1. Photometric Data

The observations used in this study consist of the published photometric data of Kooreman (1965) as well as our $UBV(RI)_C$ measurements. The historical data were obtained from JD 2,429,729 to JD 2,433,411 and comprise 90 measurements made with photographic plates at the

[1] Based partially on observations made at Laboratório Nacional de Astrofísica/CNPq, Brazil, and Cerro Tololo Inter-American Observatory (CTIO), Chile.

Leiden Observatory. We have transformed the original brightness of V529 CrA (in step units) to photographic magnitudes using the provided magnitude versus step relation from comparison stars. These data are listed in Table 1.

The $UBV(RI)_C$ measurements were obtained using the facilities of the Laboratório Nacional de Astrofísica (LNA/CNPq), Brazil. Two photometers (FOTEX and FOTRAP) were used at the 0.6 m Zeiss and 1.6 m Boller & Chivens telescopes. The FOTEX is a conventional one-channel UBV photometer, while FOTRAP uses a high-speed (1200 rpm) rotating filter wheel which allows quasi-simultaneous photometry in the $UBV(RI)_C$ bands (Jablonski et al. 1994). The photomultipliers used were an EMI 9789QA in the FOTEX and a Hamamatsu R943-02 in the FOTRAP, with both photomultipliers thermoelectrically cooled and operated in the pulse counting mode. Observations of photometric standard stars (Landolt 1973; Graham 1982) were carried out on some nights in order to correct for the effects of atmospheric extinction and transform the instrumental magnitudes to the $UBV(RI)_C$ system, as well as to calibrate two comparison stars (used for making differential photometry on nights without or with poor photometric calibration). In Table 2 we list the data of V529 CrA together with the mean values for the comparison stars (see finding chart; Fig. 5). The associated uncertainties are indicated in columns (7)–(11) and take into account the errors due to photon noise in the measurements of the variable and comparison stars and errors associated with the transformation to the standard system.

2.2. Spectroscopic Data

The spectroscopic observations of V529 CrA were obtained on two occasions (1985 July 23 and 1986 June 24) with the Boller & Chivens spectrograph on the 1 m Yale telescope of the Cerro Tololo Inter-American Observatory (CTIO), Chile. The detector used in 1985 was a GEC CCD, while in 1986 we used the 2D-Frutti. The wavelength coverage is 4500–7000 Å in 1985 and 3900–6800 Å in 1986, with a resolution of about 5 Å in both cases. Another spectrum of V529 CrA was collected on 1999 May 25 with the coudé spectrograph at the 1.6 m telescope of the LNA/CNPq, Brazil. A 600 line mm^{-1} grating and a back-illuminated SITe CCD (1024 × 1024 pixels, 24 × 24 μm^2) were used,

TABLE 1

THE LEIDEN PHOTOMETRY OF V529 CrA

JD (2,400,000+)	m_{pg}	JD (2,400,000+)	m_{pg}	JD (2,400,000+)	m_{pg}
29,729.6......	13.23	30,602.3......	12.89	31,287.2......	13.08
29,735.6......	13.12	30,606.3......	13.34	31,289.3......	13.02
29,787.3......	12.20	30,607.3......	13.64	31,292.2......	13.02
29,791.6......	12.32	30,642.3......	12.18	31,294.3......	12.72
29,794.5......	12.58	30,875.3......	14.17	31,310.3......	13.40
29,807.4......	13.30	30,877.3......	14.17	31,314.3......	13.22
29,813.4......	12.20	30,913.3......	14.68	31,317.4......	12.20
29,817.4......	12.89	30,927.3......	14.60	31,320.3......	11.64
30,085.6......	14.68	30,930.3......	14.68	31,323.4......	12.41
30,089.5......	14.80	30,932.3......	14.68	31,326.3......	12.41
30,142.5......	14.46	30,965.3......	14.60	31,328.3......	12.89
30,149.5......	14.60	30,970.3......	14.50	31,342.3......	12.32
30,163.3......	14.68	30,973.3......	14.68	31,345.3......	11.92
30,166.3......	14.33	30,989.3......	14.60	31,350.3......	12.53
30,218.3......	14.50	30,993.3......	14.50	31,371.3......	12.32
30,247.3......	14.60	30,998.3......	14.68	31,555.5......	14.08
30,249.3......	14.68	31,000.3......	14.68	31,558.5......	14.17
30,257.3......	14.60	31,017.2......	14.50	31,560.5......	14.17
30,280.3......	14.50	31,171.6......	14.00	31,590.4......	14.68
30,282.2......	13.88	31,178.6......	11.80	31,594.4......	14.68
30,286.3......	13.78	31,203.5......	11.92	31,612.3......	14.60
30,473.5......	11.80	31,204.4......	12.20	31,615.3......	14.68
30,500.4......	12.32	31,208.4......	12.55	31,617.4......	14.80
30,544.3......	12.42	31,233.6......	12.55	31,668.3......	14.68
30,549.5......	12.41	31,238.5......	12.95	31,671.3......	14.48
30,553.3......	12.89	31,264.4......	13.64	31,675.3......	14.60
30,556.3......	13.02	31,268.4......	13.64	31,678.3......	14.60
30,559.4......	13.34	31,269.3......	13.78	32,445.3......	14.68
30,574.3......	12.41	31,281.2......	12.53	32,765.4......	12.32
30,576.3......	12.32	31,284.3......	12.75	33,411.2......	14.26

TABLE 2

UBV(*RI*)$_C$ Photometry of V529 CrA

HJD	V	$U-B$	$B-V$	$V-R_C$	R_C-I_C	σ_V	σ_{U-B}	σ_{B-V}	σ_{V-R}	σ_{R-I}	Comments[a]
2,446,176.66100......	13.372	...	1.219	...	...	0.019	...	0.041	...	...	A
2,446,236.72407......	13.589	1.060	1.347	...	...	0.067	0.122	0.079	...	...	A
2,446,283.63332......	13.397	...	1.403	...	...	0.022	...	0.038	...	...	A
2,446,352.44459......	12.308	1.025	1.164	...	...	0.013	0.041	0.022	...	...	A
2,446,550.76098......	11.758	0.686	0.769	...	...	0.010	0.014	0.011	...	...	B
2,446,552.84247......	11.916	...	0.876	...	...	0.010	...	0.011	...	...	B
2,446,553.83815......	11.957	0.790	0.940	...	...	0.011	0.026	0.012	...	...	B
2,446,554.84278......	11.993	...	1.004	...	...	0.012	...	0.013	...	...	B
2,450,289.57788......	12.172	0.695	0.912	0.489	0.468	0.013	0.078	0.030	0.019	0.014	A
2,450,290.53991......	12.040	0.523	0.832	0.497	0.419	0.018	0.085	0.042	0.022	0.020	A, C
2,450,291.58651......	11.899	0.418	0.743	0.442	0.389	0.025	0.098	0.043	0.033	0.030	A, C
2,450,317.52268......	11.483	0.339	0.668	0.359	0.373	0.022	0.054	0.022	0.022	0.018	A, C, D
2,450,318.52982......	11.427	0.406	0.679	0.417	0.424	0.031	0.064	0.031	0.034	0.036	A, C
2,450,319.49922......	11.505	0.625	0.719	0.467	0.357	0.039	0.105	0.039	0.032	0.025	A
2,450,320.53951......	11.386	0.495	0.802	0.412	0.412	0.042	0.114	0.042	0.034	0.030	A, C
2,450,321.54386......	11.502	0.422	0.889	0.480	0.382	0.032	0.132	0.057	0.040	0.030	A
2,450,349.43898......	11.703	...	1.061	0.513	0.443	0.021	...	0.037	0.025	0.021	A, C
2,450,361.49328......	12.427	0.942	0.990	0.557	0.479	0.024	0.078	0.036	0.017	0.015	A, C
2,450,362.45983......	12.088	0.896	0.871	0.507	0.438	0.024	0.067	0.030	0.012	0.015	A
C1	8.890	1.499	1.403	0.735	0.664	0.010	0.020	0.010	0.010	0.010	A
C2	10.223	1.469	1.379	0.734	0.675	0.014	0.030	0.015	0.010	0.010	A

[a] A: 0.6 m telescope; B: 1.6 m telescope; C: differential photometry with respect to comparison stars; D: average of two measurements.

providing a spectral coverage of 3915–4355 Å with about 1 Å resolution. This spectrum was taken after moonset.

The reduction of these spectra was carried out in a standard way, with the CTIO's spectra being reduced at CTIO headquarters using the TVRED package, while the spectrum collected at LNA was reduced with IRAF[2] software, installed at the Sun workstations of the Astrophysics Division of Instituto Nacional de Pesquisas Espaciais.

3. ANALYSIS AND DISCUSSION

3.1. Photometric Data

In order to analyze the *UBV*(*RI*)$_C$ photometry together with historical data, we used the B magnitudes from our data since this is the closest passband to those giving photographic magnitudes. The search for periodicities was carried out using a discrete Fourier transform algorithm (Deeming 1975) together with the CLEAN procedure of Roberts, Lehár, & Dreher (1987). Initially, we applied this algorithm to all data in order to search for long-term modulations, since a variation on a timescale of several hundred days is clearly evident in the historical data (Fig. 1). The result of this analysis indicates a period of 761.5 days for the long-term modulation. Besides this period, a significant peak is also seen at 23.6 days.

The presence of power excess in higher frequencies motivated us to do a more refined analysis of the photometric data. This was done by taking into account the fact that the RV Tauri variables normally present larger amplitudes for the rapid variation at maximum of the longer modulation; thus we analyzed separately the data with $B < 13.7$ and in the phase interval 0.8–1.2 of the 761.5 day modulation. The analysis confirmed the period of 23.571 days as dominant in this interval. On the other hand, a power spectrum of the remaining points shows little evidence of this period, which confirms that the rapid oscillations are mainly restricted to the maximum of the longer modulation.

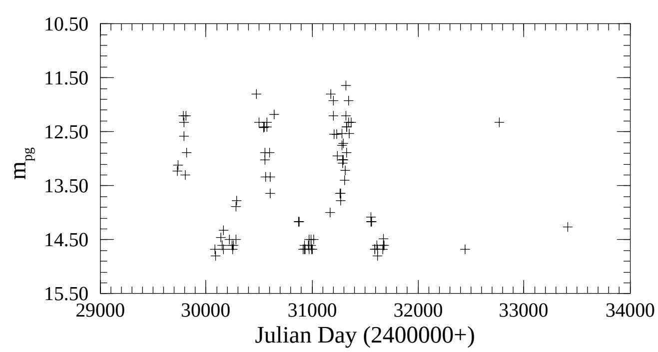

Fig. 1.—Historical photographic data of V529 CrA

[2] IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Two additional methods for the determination of periodicities were also applied to the data: the phase dispersion minimization (PDM) as implemented in IRAF and the Lomb-Scargle Fourier method for unequally spaced data (Lomb 1976; Scargle 1982). These algorithms confirm the results above.

The folded light curves for the periods of 761.5 and 23.571 days are shown in Figures 2*a* and 2*b*, respectively. The curve for twice the period of 23.571 days (47.142 days) is shown in Figure 2*c*. The presence of alternating deep/shallow minima behavior as seen in RV Tauri variables is evident.

The ephemerides for the periods of 761.5 and 47.142 days can be written as

$$T_{\max}(\mathrm{JD}) = 2{,}434{,}340(\pm 7) + 761.5(\pm 1.0)E \ ,$$

$$T_{\min}(\mathrm{JD}) = 2{,}435{,}415(\pm 1) + 47.142(\pm 0.004)E \ ,$$

where E is cycle number counted from the reference epoch.

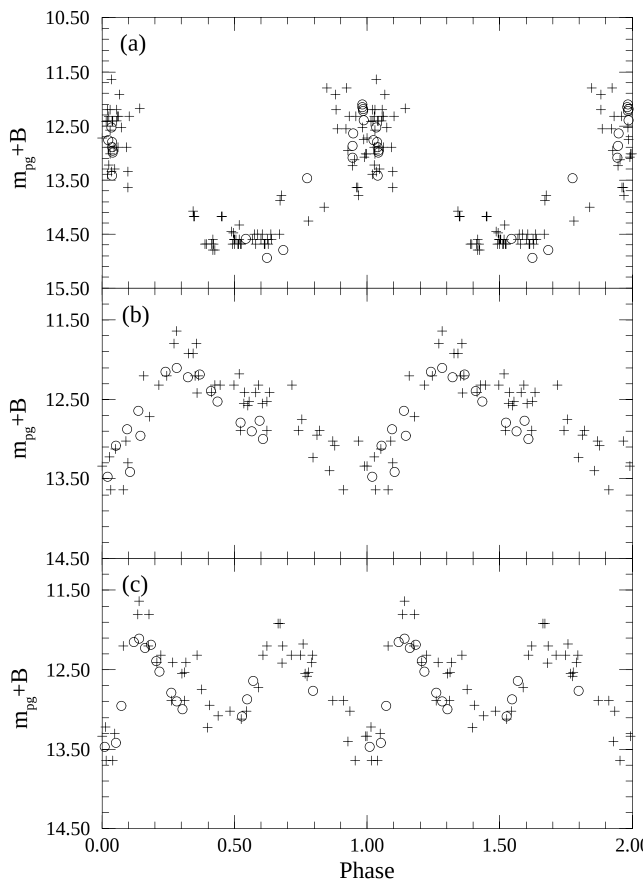

FIG. 2.—Photometric data of V529 CrA folded on the periods (*a*) 761.5 days, (*b*) 23.571 days, and (*c*) 47.142 days. Plus symbols indicate photographic data and open circles our B data. Plots *b* and *c* were done using only the points with $B < 13.7$ and in the phase interval 0.8–1.2 of the 761.5 day modulation. The phases in plot *b* were computed using the ephemeris of the 47.142 day period.

A detailed analysis of the color behavior is not possible with our $UBV(RI)_C$ photometry since the observations do not cover all phases of the 47.142 day period. However, the data are sufficient to show that there is a tendency for the color curves (more visible in the $B-V$, because of the larger number of points) to be bluest when the V light curve is brighter. Such behavior is seen in the RV Tauri variables (see, e.g., Pollard et al. 1996), although in these stars the bluest colors occur in the rising part of the maximum. The verification of this characteristic in V529 CrA requires a better photometric coverage.

The RV Tauri variables are also known to exhibit large infrared excesses (see, e.g., Gehrz & Woolf 1970; Gehrz 1972; Gehrz & Ney 1972; Lloyd Evans 1985; Goldsmith et al. 1987; Nook & Cardelli 1989). This motivated us to do a search in the *IRAS* sources. In fact, V529 CrA is a weak *IRAS* source with the observed fluxes of 0.43 Jy (12 μm) and 0.32 Jy (25 μm). The fluxes at 60 and 100 μm are indicated as upper limits. The fact that the fluxes at 60 and 100 μm are upper limits does not permit a more detailed comparison with other RV Tauri stars; however, the value of the $12-25$ μm index of V529 CrA is comparable to those of other RVb variables. The presence of infrared excess in stars is normally associated with an extended circumstellar dust shell.

3.2. Spectroscopic Data

The spectrum of V529 CrA collected on 1986 June 24 is shown in Figure 3. On this occasion the object was near the maximum of the 761.5 day modulation (phase 0.11) and at phase 0.38 of the 47.142 day modulation. Hα and Hβ as well as several other lines such as Ca II ($\lambda\lambda$3933.7, 3968.5), Fe I+Fe II λ4384, Fe I ($\lambda\lambda$5269.5, 5324.2, 5397.1), Fe II ($\lambda\lambda$4923.9, 5018.4), and the triplet of Mg I in 5167.3–5183.6 Å are seen in absorption in this spectrum. The spectrum obtained on 1985 July 23 corresponds to phases 0.67 (761.5 days) and 0.26 (47.142 days) and also shows the lines of Hβ, Hα, Fe II λ4923.9, Fe II λ5018.4, Fe I in 5269.5, 5324.2, and 5397.1 Å, and the triplet of Mg I. The spectrum of 1999 May 25 corresponds to phases 0.30 (761.5 days) and 0.47 (47.142 days). It shows clearly a strong line of Sr II λ4077.7 as well as several lines of Fe I ($\lambda\lambda$4005.2, 4045.8, 4063.6, 4143.9, 4271.8, 4352.7), Mn I in 4033.1 and 4034.5 Å, and Ca I λ4226.7 (Fig. 4). This spectrum also shows a radial velocity of -160 km s^{-1}. This velocity is larger than is seen, for example, in the RV Tauri stars AR Sgr and V453 Oph, which are the objects with the largest velocities in the sample studied by Pollard et al. (1997).

A comparison of the intensities of the Balmer, Ca II, and Fe lines and of the G band in the spectra collected on 1986 June 24 and 1985 July 23 indicates a spectral type in the range G5–K0 for both spectra (Jacoby, Hunter, & Christian 1984). For the spectra obtained on 1999 May 25, the relative strength of the line Sr II λ4077.7 to Fe I λ4045.8 indi-

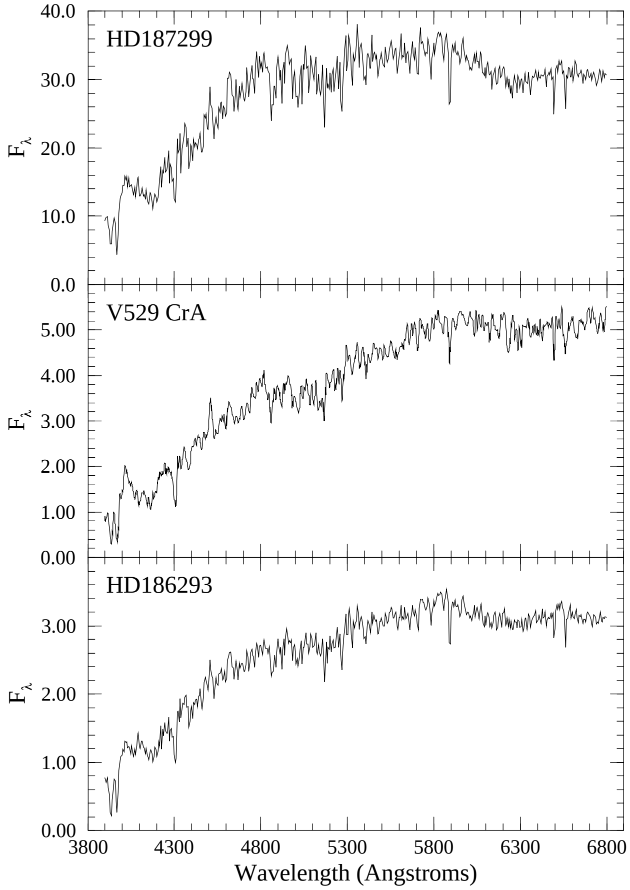

FIG. 3.—Spectrum of V529 CrA obtained on 1986 June 24 (*middle frame*). The top and bottom frames show the spectra of two spectrophotometric standard stars from the list of Jacoby et al. (1984): HD 187299 (spectral type G5 I) and HD 186293 (spectral type K0 I). The fluxes are in units of 10^{-14} ergs cm^{-2} s^{-1} Å^{-1} (V529 CrA) and 10^{-12} ergs cm^{-2} s^{-1} Å^{-1} (standard stars).

cates that the star is a supergiant (luminosity class Ia) with a spectral type K0–K3 (Yamashita, Nariai, & Norimoto 1977). The presence of numerous and relatively strong metallic lines in absorption in these spectra suggests a classification in the A Preston type (Preston et al. 1963; Cardelli & Howell 1989).

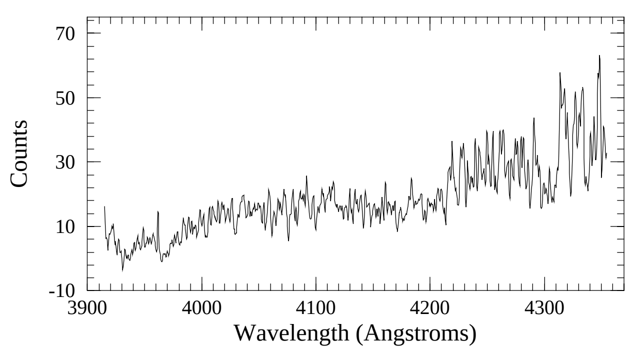

FIG. 4.—Spectrum of V529 CrA obtained on 1999 May 25 (not calibrated in flux).

4. CONCLUSIONS

As the formal period of a RV Tauri variable is defined by the time interval between adjacent deep minima (Kholopov et al. 1985), we adopt the value of 47.142 days for the period of the short time variations in V529 CrA. The folded light curve for this period (Fig. 2*c*) shows the presence of shallow and deep minima typical of the RV Tauri class of variables. On the other hand, the presence of a long-term modulation with a period of 761.5 days (Fig. 2*a*) excludes a classification as W Vir type (as could be suggested by the curve shown in Fig. 2*b*) and indicates that V529 CrA belongs to the RVb photometric subclass. The classification of V529 CrA as an RV Tauri variable is also supported by the smaller scatter in the light curve of the 47.142 day period. The average of all dispersions (calculated in intervals of 0.1 in phase) for this period gives $\sigma \simeq 0.21$, while for the period of 23.571 days it is $\sigma \simeq 0.26$. The spectroscopic characteristics presented are compatible with the A Preston type. Figure 5 shows a finding chart for V529 CrA, obtained from the Digitized Sky Survey (SkyView).[3]

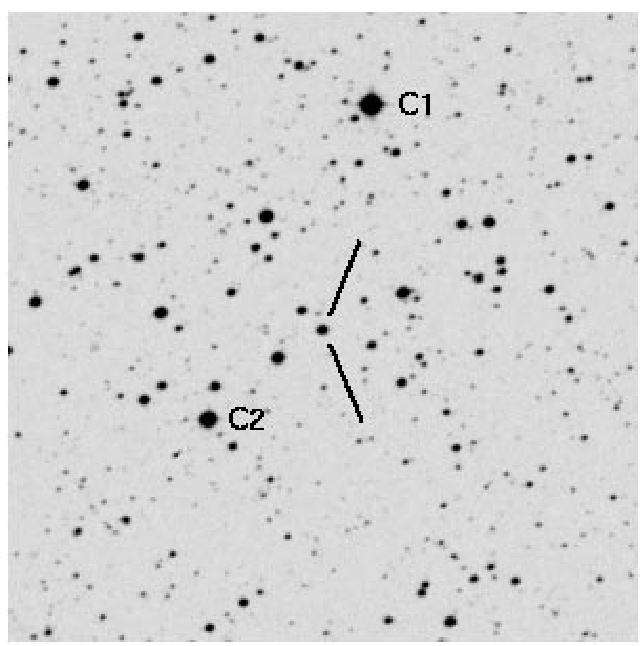

FIG. 5.—An 8'.5 × 8'.5 finding chart for V529 CrA. North is up and east to the left. C1 and C2 are comparison stars.

[3] SkyView was developed under NASA ADP grant NAS S-32068 and under the auspices of the High Energy Astrophysics Science Archive Research Center (HEASARC) at the GSFC Laboratory for High Energy Astrophysics.

We are grateful to the LNA and CTIO staffs for the observing assistance during the observing runs and M. P. Diaz for helping with the spectrophotometric calibration stars. We thank the referee for the valuable comments which permitted us to improve the paper considerably. D. Cieslinski and G. R. Hickel acknowledge the support from CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo).

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