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Spottedness of the Emission-Line Dwarf Stars BF CVn, DT Vir, EQ Vir, and V1396 Cyg from Photoelectric and Photographic Observations

I. Yu. Alekseev and N. I. Bondar'

Crimean Astrophysical Observatory, p/o Nauchnyi, Crimea, 334413 Ukraine

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Abstract—Overall light curves of the spotted red dwarfs BF CVn, DT Vir, EQ Vir, and V1396 Cyg are constructed. The photometric maxima and the spottedness of their photospheres are estimated. Both stellar hemispheres are generally covered with spots, their effective areas are 10–20% of the visible hemisphere, and their temperatures are 300–900 K lower than the photospheric values.

INTRODUCTION

Spottedness is a common phenomenon, especially among late-type, low-luminosity stars. By now, algorithms for estimating the total areas and temperatures of the spots that cover the surfaces of spotted stars from their multicolor photoelectric observations have been developed (Vogt 1975, 1981; Torres and Ferraz-Mello 1973; Poe and Eaton 1985; Budding 1977). Normally, observations performed over one season are considered. These observations, strictly speaking, provide data only on differential spottedness, i.e., on the difference between the areas of the spots covering the stellar hemispheres with maximum and minimum spottedness. Such an analysis cannot describe the seasonal variations in maximum light detected in a number of stars. Chugainov (1976) and Vogt (1975, 1981) proposed a model in which both stellar hemispheres are more or less uniformly covered with dark spots, but the total spot area in one of them is greater than in the other. This model accounts for the observed rotational modulation of the stellar flux, while changes in the configuration of the spots and their total area produce variations in maximum light of the star from season to season. We can then estimate the fraction of the stellar surface covered with spots by determining from a fairly extended series of observations its photometric maximum, at which the brighter hemisphere may be completely free of spots. Note that this is a lower limit on the spottedness. Such an analysis was first performed by Chugainov (1976) and Vogt (1975, 1981) for the star BY Dra. However, these authors used the *B–V* (Chugainov 1976) and *V–R* (Vogt 1981) colors which, according to Poe and Eaton (1985), are affected appreciably by limb darkening and chromospheric emission. From this point of view, measurements in *V* and *I* are optimal.

In this study, we do not make any assumptions about the spot configuration and use *UBVRI* observations and published data to estimate the maximum spottedness for four flare stars: DT Vir (=Gl 494 = BD+13°2618 = Vys 140 = Ross 458), BF CVn (= Gl 490A = BD+36°2322 = Vys 298), EQ Vir (= Gl 517 = BD–07°3646 = Vys 145 = HD 118100), and V1396 Cyg (= Gl 815A = BD+40°883 = Vys 200). The basic parameters of the program stars are given in Table 1.

We chose the initial epochs in the ephemerides arbitrarily and determined the effective temperature of

Table 1. Basic parameters of the program stars

Star	Spectral type	V	Ephemeris	$T_{\rm eff}$
DT Vir	M1.5e [1]	$9^m.79$ [1]	9108.0 + 1.535*E* [6]	3550 [9]
BF CVn	M1.5e [2]	10.56 [4]	9027.0 + 3.17*E* [4]	3500 [10]
EQ Vir	K7e [3]	9.25 [5]	8994.0 + 3.96*E* [7]	4075 [5]
V1396 Cyg	M3e [1]	10.26 [1]	8875.0 + 3.276*E* [8]	3400

Note: [1] Pettersen (1976); [2] Joy and Abt (1974); [3] Pettersen (1991); [4] Pettersen (1980b); [5] Pettersen (1989); [6] Torres*et al.* (1983); [7] Ferraz-Mello and Torres (1971); [8] Bopp and Fekel (1977); [9] Pettersen (1980a); [10] Spiesman and Hawley (1986).

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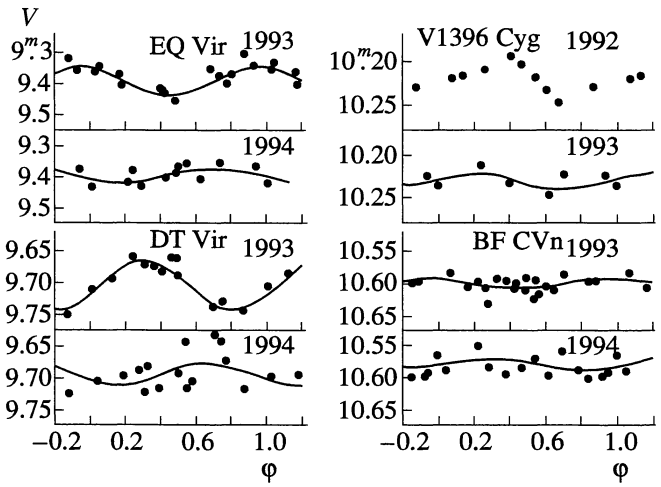

Fig. 1. *V* light curves of the program stars.

V1396 Cyg from the color indices of the star using the calibration of Johnson (1966).

PHOTOELECTRIC OBSERVATIONS

We carried out all our observations between 1992 and 1994 using the 1.25-m Crimean Astrophysical Observatory telescope (AZT-11). The detector was the *UBVRI* photometer/polarimeter of Piirola (1984) operating in the photometry mode. Three to four successive sets of measurements were made for each star on a single night, each consisting of a sequence of pointings at the object, the comparison star, and the check star; four readings with an integration time of 10 s each were taken during each pointing. Data on the comparison stars, check stars, and observing seasons are given in Table 2.

The *V* light curves of the program stars are shown in Fig. 1. Note that the shape of the light curves of DT Vir, EQ Vir, and V1396 Cyg changes markedly from season to season. We detected no statistically significant light variations in BF Cvn.

ANALYSIS OF SURFACE-BRIGHTNESS VARIATIONS

In order to reliably estimate the absolute photometric maxima of the stars and their spottedness, we must consider sufficiently extended series of observations. For this purpose, we used our photoelectric *B* observations, published photoelectric *B* photometry (Pettersen 1979, 1980b; Spiesman and Hawley 1986; Ferraz-Mello and Torres 1971; Krzeminski 1969; Chugainov 1973, 1974; Bopp and Espenak 1977; Roizman 1987; Anderson 1979; Grenon and Rufener 1981; Hoffman 1980), and the magnitudes of the objects that we measured from archived plates of the Sternberg Astronomical Institute and the Odessa and Sonneberg Observatories. The techniques and results of the photographic measurements are detailed in Bondar' (1996). The light curves of the program stars are shown in Fig. 2. The open and filled circles indicate the yearly mean magnitudes as derived from the photographic data.

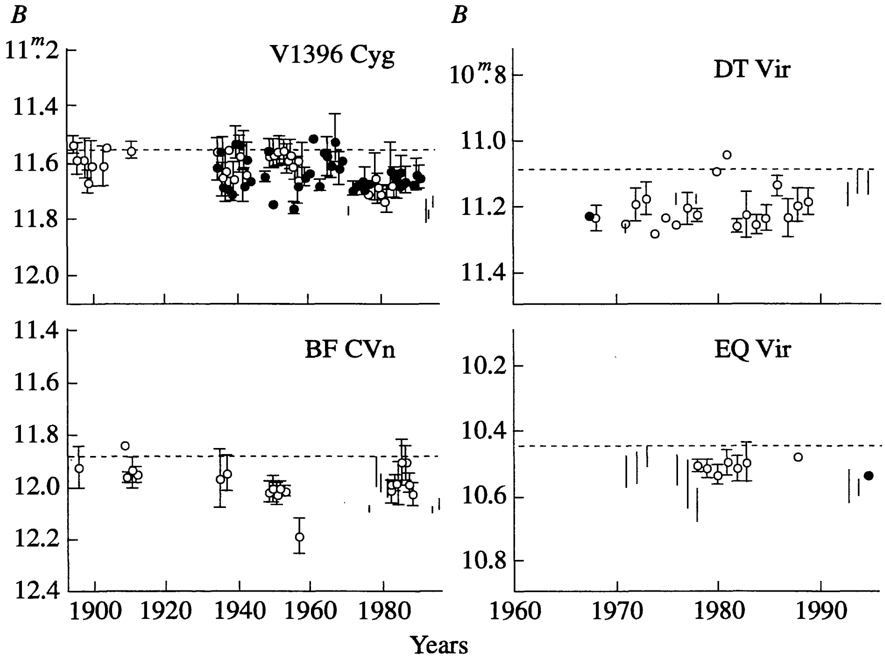

Fig. 2. Long-term light variations of the program stars from photoelectric (vertical lines) and photographic (circles) observations. The filled circles are for the Sonneberg collection of plates, and the open circles are for the Sternberg Astronomical Institute collection. The notation is also explained in the text.

Table 2. Comparison stars, check stars, and observing seasons

Star	Comparison star	V	Check star	Observing seasons
DT Vir	BD +13°2613	$10\overset{m}{.}86$	BD +13°2617	Jan–Apr. 1993, 1994
BF CVn	SAO 63287	7.75	SAO 63286	Jan–Apr. 1993, 1994
EQ Vir	BD –07°3642	7.77	BD –07°3643	Jan–Apr. 1993, 1994
V1396 Cyg	SAO 509394	8.33		Sep.–Oct. 1992, 1993

The rms errors of a single measurement are indicated by bars; their absence means that one plate was used in the measurements. The photoelectric data are indicated by the vertical lines, which show the total amplitude of the photometric variability caused by rotational modulation. We can see good agreement between the photoelectric data and the plate measurements for all the objects under consideration. The light curves all exhibit seasonal surface-brightness variations. The level of maximum light in each diagram is indicated by the dashed line. Its value was determined from the photoelectric data and is confirmed on long time intervals by photographic measurements. We took the observed photometric maxima of the program stars ($10\overset{m}{.}07$ for V1396 Cyg, $9\overset{m}{.}65$ for DT Vir, $10\overset{m}{.}46$ for BF CVn, and $9\overset{m}{.}25$ for EQ Vir) to be the light level of the unspotted photosphere $V_{\max}$.

The amplitudes of rotational modulation in V1396 Cyg were small—~$0\overset{m}{.}02$–$0\overset{m}{.}03$, except for the 1966 season, when ΔV reached $0\overset{m}{.}10$. For DT Vir, the amplitude ΔV was close to $0\overset{m}{.}07$. There was virtually no rotational modulation in BF CVn, except for the 1978–1991 seasons ($\Delta V \sim 0\overset{m}{.}07$–$0\overset{m}{.}10$), when great variations in the mean magnitude of the star from season to season were also observed. EQ Vir almost always exhibited rotational modulation with amplitudes ~$0\overset{m}{.}10$–$0\overset{m}{.}15$. The greatest light declines relative to $V_{\max}$ are ~$0\overset{m}{.}20$ for all our program stars.

The B–V color indices of all the four stars vary only slightly. For the other colors, we have only separate measurements. The color indices are given in Table 3.

DETERMINATION OF THE SPOTTEDNESS PARAMETERS

We used the following relation (Vogt 1981) to determine the spottedness parameters:

$$\Delta m_\lambda = -2.5\log\{1-(1-\beta_\lambda)[(1-u_\lambda)G + u_\lambda J]/(1-u_\lambda/3)\}, \qquad (1)$$

where β_λ is the ratio of the surface brightnesses of the spot and the photosphere,

$$\pi G = \iint\limits_{\substack{\text{spotted}\\ \text{area}}} \cos\alpha\sin\theta\,d\theta\,d\phi \qquad (2)$$

$$\pi J = \iint\limits_{\substack{\text{spotted}\\ \text{area}}} \cos^2\alpha\sin\theta\,d\theta\,d\phi. \qquad (3)$$

Here, G is the area of the spot projection onto the plane of the sky in fractions of the visible stellar hemisphere, and J/G is the cosine of the angular distance of the spot center from the disk center averaged over the spot area (Vogt 1981). The magnitudes Δm are measured from the light level of the unspotted photosphere.

It follows from relation (1) that the parameters of the spotted regions cannot be unambiguously determined from observations performed only at one wavelength. Therefore, in addition to the amplitude of light variations ΔV, the amplitude of color variations [usually $\Delta(V$–$R)$ and $\Delta(V$–$I)$ is commonly determined during multicolor observations of spotted stars. However, the color indices vary only slightly, with an amplitude of ~$0\overset{m}{.}01$–$0\overset{m}{.}03$, and they are rather difficult to determine reliably. Davidson and Neff (1977) found a linear relation between the B, R, and I-light variations in the classical spotted star BY Dra and its light variations in V. Similar relations were obtained by Gershberg *et al.* (1991) for EV Lac (M4.5) and by Alekseev and Shakhovskaya (1995) for MS Ser (K2), V775 Her (K0), and FK Ser (K5). We applied a similar procedure and considered statistical relations between the magnitude differences of the objects and the comparison stars in U, B, R, and I and the corresponding difference in V; we also found them to be linearly related. Thus, knowing

Table 3. Color indices of the program stars

Star	U–B	B–V	V–R	V–I	References
DT Vir	$1\overset{m}{.}12$	$1\overset{m}{.}44$	$1\overset{m}{.}48$	$2\overset{m}{.}64$	[1]
BF CVn	1.16	1.42	1.47	2.63	[4]
EQ Vir	1.05	1.18	1.13	1.86	[5]
V1396 Cyg	1.09	1.50	1.50	2.70	[1]

Note: References are given in the notes to Table 1.

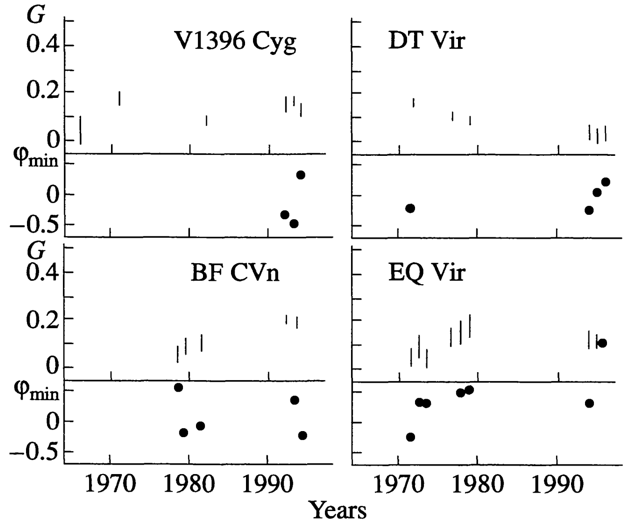

Fig. 3. Areas and phases of the greatest visibility of the spotted regions versus time. The notation is the same as in Fig. 2.

this relation, we can determine the spottedness parameters for our objects by using the *V* light curve alone. The angular coefficients of linear regression and the correlation coefficients between these quantities (r) are given in Table 4.

These values are in good agreement with the values obtained for MS Ser, FK Ser, and EV Lac by Alekseev and Shakhovskaya (1995) using the same equipment and the same techniques. The angular coefficients of linear regression $\Delta B/\Delta V$, $\Delta R/\Delta V$, and $\Delta I/\Delta V$ for different stars differ only slightly, whereas $\Delta U/\Delta V$ are markedly different due possibly to the difference in the contributions of chromospheric emission.

Of the ratios $\Delta U/\Delta V$, $\Delta B/\Delta V$, $\Delta R/\Delta V$, and $\Delta I/\Delta V$, the latter is determined most reliably. In addition, the *V* and *I* bands are free of the contribution from microflares ($\Delta U/\Delta V$), chromospheric emission in Hα ($\Delta R/\Delta V$), and limb darkening.

We used the method proposed by Gershberg *et al.* (1991) to determine β_λ. These authors considered statistical relations between the absolute magnitudes reduced to a single radius,

$$m'_\lambda = m_\lambda + (M_V - m_V) + 5\log(R/R_0) \qquad (4)$$

for a number of red dwarfs of spectral types K5–M6.5. By definition, m'_λ is related (linearly) only to the logarithm of the surface brightness of the star at a given wavelength. Variations in these quantities at different wavelengths are linearly related to each other; specifically,

$$\Delta I'/\Delta V' = 0.35. \qquad (5)$$

Assuming that the energy distribution in the spot spectrum corresponds to the energy distribution in the photospheric spectrum of a cooler star, we can write

$$\log\beta_I/\log\beta_V = 0.35. \qquad (6)$$

Similar relations also hold for the other photometric bands (Gershberg *et al.* 1991).

Let us assume that the following approximate relation is valid:

$$G = 2J/3. \qquad (7)$$

For the *V* and *I* bands, we then have relations of the form

$$\Delta V = -2.5\log(1-(1-\beta_V)G),$$

$$\Delta I = -2.5\log(1-(1-\beta_V^{0.35})G),$$

from which we can easily derive G and β_V (and, accordingly, the spot temperature). In this formalism, the accuracy of determining G and the temperature is 0.01 and 30 K, respectively. Note that the ratios $\Delta U/\Delta V$, $\Delta B/\Delta V$, and $\Delta R/\Delta V$ calculated in the approximation (7) are equal to the observed values, within the limits of the measurement errors (Table 5).

In Fig. 3, the effective spot areas G at minimum and maximum spot visibility and the phases of minimum light are plotted against time. According to our estimates, both hemispheres of all the objects under consideration are generally covered with spots.

On V1396 Cyg, the spots are distributed in longitude more or less uniformly. The spotted area is 10–20% of the stellar surface. The temperature of the spotted regions is 500 K lower than that of the unspotted photosphere.

For BF CVn, we found that the spotted regions are approximately 860 K cooler than the photosphere, and that the spot area may reach 20% of the visible hemisphere, for example, in 1976. On the average, however, 10% of both stellar hemispheres are covered with spots. The maximum difference between $G_{\max}$ and $G_{\min}$ is

Table 4. Statistical relations between the magnitude differences of the object and the comparison star in *U*, *B*, *R*, *I* and in *V*

Star	$\Delta U/\Delta V$	r	$\Delta B/\Delta V$	r	$\Delta R/\Delta V$	r	$\Delta I/\Delta V$	r
DT Vir	0.64 ± .16	0.79	0.98 ± .06	0.99	0.84 ± .08	0.96	0.70 ± .01	0.96
BF CVn	1.47 ± .30	0.58	0.99 ± .05	0.94	0.92 ± .15	0.67	0.69 ± .03	0.96
EQ Vir	1.84 ± .59	0.66	1.16 ± .04	0.99	0.82 ± .05	0.98	0.63 ± .03	0.99
V1396 Cyg	1.62 ± .36	0.64	1.30 ± .07	0.96			0.57 ± .04	0.92

Table 5

Star	$\Delta B/\Delta V$		$\Delta R/\Delta V$		$\Delta I/\Delta V$	
	1	2	1	2	1	2
DT Vir	0.98(.06)	1.03	0.84(.08)	0.90	0.70(.01)	0.70
BF CVn	0.99(.05)	1.04	0.92(.15)	0.90	0.69(.03)	0.68
EQ Vir	1.16(.04)	1.06	0.82(.05)	0.86	0.63(.03)	0.62
V1396 Cyg	1.30(.07)	1.08		0.82	0.57(.04)	0.55

Note: (1) observed values; (2) theoretical values (rms deviations are given in parentheses).

Table 6. Temperatures and maximum effective areas of the spotted regions

Star	Spectral type	$T_{\rm phot}$, K	Maximum spot area, %	$T_{\rm spot}$, K	$(T_{\rm phot} - T_{\rm spot})$, K
Sun	G2V	6050	0.5	4240	1810
VY Ari	G9eIV	4860	31	3040	1820
V775 Her	K0e	4900	42	3570	1330
MS Ser	K2e	4960	13	3020	1940
OU Gem	dK3e	4700	12	2800	1900
FK Ser	dK5e	4100	17	2500	1600
EQ Vir	dK7e	4250	24	3260	900
V1005 Ori	dM0.5e	3580	18	2680	900
DT Vir	dM1.5e	3550	17	2640	910
BF CVn	dM1.5e	3500	19	2640	860
V1396 Cyg	dM3e	3400	20	2900	500
EV Lac	dM4.5e	3300	40	3050	250

10% of the stellar surface; in general, however, the spots are also uniformly distributed in longitude.

A similar pattern of spottedness is also observed in DT Vir: the spot area is 10–15%, the difference between $G_{\rm max}$ and $G_{\rm min}$ may reach 7%, and the spots are 900 K cooler than the surrounding photosphere.

EQ Vir exhibits the greatest spottedness. In general, 5–10% (brighter hemisphere) and 10–15% (darker hemisphere) of this star are covered with spots. The maximum spottedness may reach 24% of the surface, and the maximum difference between $G_{\rm max}$ and $G_{\rm min}$ may be as large as 15%. The spot temperature is also 900 K lower than the photospheric temperature.

CONCLUSION

Thus, we have established that spots occupy a substantial fraction of the surfaces of all the objects under consideration. Both stellar hemispheres are generally covered with spots, and the spotted area is 10–20% of the surface or more. The decrease in the amplitude of rotational modulation of the stellar flux in some seasons is commonly associated not so much with the disappearance of spots, as with their more uniform distribution in longitude. Our results are summarized in Table 6, which gives the maximum observed areas of the spots and their mean temperatures for our objects and for a number of red dwarf stars, for which we carried out a similar analysis, along with the parameters of solar spots (Allen 1977).

The temperatures of the spotted regions on hot G–K (up to K5) stars are 1500 to 2000 K lower than the temperature of the surrounding photosphere. Here, the temperature difference between the spot and the photosphere is independent of spectral type. For fairly cool (later than K5) stars, this difference decreases from 1000 K to 300 K toward later spectral types. The spot temperature in this case is independent of the spectral type of the star and equal to ~3000 K. A similar tendency was noted by Vogt (1983) for a number of spotted giants and subgiants.

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