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Flare activity and BY-Draconis-type variability on the late-type dMe star Gliese 867 B

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Summary. We report on a search for flaring and BY Draconis type variability on the M-dwarf Balmer emission line star, Gliese 867 B. The time-averaged flare energy in the Johnson U-band is similar to that measured in 1977 and 1978. A typical wave-like variation of 0.15 magnitudes, seemingly due to rotational modulation of large spotted areas, was observed in the V-band with a period 1.95 days.

Key words: flare star – dMe dwarf – BY-Dra type variability – flare equivalent duration – flare energy

1. Introduction

The dMe flare stars, or UV-Ceti type stars, are a set of late-type red dwarf stars which undergo intense brightenings, or flares. These stars are characterised in their quiescent state by the presence of chromospheric emission lines, such as the hydrogen Balmer lines and Ca H & K. Quite often in the star's quiescent state, a periodic light variability with amplitude of the order of one tenth of a magnitude is observed which can be attributed to large spots (see recent reviews by Byrne, 1983 and Vogt, 1983).

This paper is one of a series in which we describe both optical and IUE spectroscopy, optical photometry and X-ray observations of M dwarf stars of differing levels of activity (Byrne 1979, Byrne and McFarland 1980, Byrne 1981, Butler et al., 1981, Byrne et al., 1984a, Byrne et al., 1984b, Doyle and Butler 1985, Byrne et al., 1985 and Doyle et al., 1985). The object of this work has been to try to establish levels of optical activity, e.g. flare energetics, rotation rates, chromospheric radiative loss rates, and to test this data for any correlations with other parameters, e.g. the bolometric magnitude or the quiescent X-ray flux. In this work both the most active objects and those which show less spectacular activity levels have been looked at. Here, we look again at Gl 867B, which has been studied previously in 1977 and 1978 (Byrne 1979, Byrne and McFarland 1980). This star is a visual binary with a separation of 22 arc seconds between the A and B components. The B component has been classified as dM4.5e (Gliese 1969) and dM3e (Joy and Abt 1974).

2. Observations

The observations reported here were made over the period 23 September–12 October 1981. Photometry was carried out on the 75 cm telescope at the South African Astronomical Observatory at Sutherland using a photometer belonging to the University of Cape Town (UCTP), similar to that described by Nather and Warner (1971). For these observations the UCTP was equipped with a red-sensitive RCA 8644 photomultiplier tube, with glass filters approximating to the Johnson UBVR system. No red-leak blocking filter was provided for the U-band nor was there a cut-off filter for the V-band. Using the red band we corrected for the red leak in U, with transformations to the Johnson system obtained through reference to Cousin's E-regions stars (Menzies et al., 1980). The accuracy of these transformations were checked through measurements made of the star Gl 735 (Byrne et al., 1984b), since measurements were made using a blue-sensitive tube on the 19 and 20 September 1981 which had well-determined transformations characteristics, while the red-sensitive tube was used during the period September 22–October 14. For this latter star good agreement was obtained for the UBV magnitudes for the two different sets of color equations. An additional check was provided from observations by Sanwal (1982) on 1 October for the two large flares observed simultaneously with us. The peak U-band flare amplitude given by Sanwal was in good agreement with our measurements as was the general shape of the two light-curves.

All the flare monitoring was in the Johnson U-band with integrations times of either 5 or 10 secs. Dates and times of monitoring can be found in Table 1. Gl 867B was also measured twice nightly (separated by approximately 20–30 mins.) in all four colors, plus two comparison stars HD 214380 and HD 214381.

Ultra-violet spectra in the wavelength regions 1100–1950 Å and 2000–3000 Å were obtained on 1 October 1981 from the International Ultra-violet Explorer (IUE) satellite. This data consisted of two low-dispersion short wavelength (SWP) exposures and one low-dispersion long wavelength (LWR) exposure. The first SWP spectrum consisted of two separate exposures each of 30 minutes duration on the same image. Processing of the data was done with the STARLINK program IUEDR (Giddings 1983). A log of the IUE data is given in Table 2.

Table 1. Flare monitoring times

Date	U.T.
1981 23/24 Sept	20 : 30–22 : 00
1/2 Oct	17 : 40–22 : 36
Total 6.43 hours	

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Table 2. Details of IUE spectra for Gl 867 B

Image No.	Date	Start time (UT)	J.D.	Exp. (mins.)
SWP 15148 A	1981 1 Oct	18 : 39 : 27	2444878.28	30.0
SWP 15148 B		19 : 15 : 59	4878.30	30.0
SWP 15149		20 : 31 : 59	4878.35	46.0
LWR 11653		19 : 56 : 37	4878.33	20.0

3. Results and discussion

3.1. Flare activity

In a total monitoring time of 6.4 h, 16 enhancements were observed. Some of these were long duration events, lasting some 10 mins. before returning to normal, e.g. see Fig. 1 for 1 Oct. at 18 : 38 UT or 19 : 20 UT. Other were spike events, usually detected a few minutes before a large flare (e.g. see Fig. 1 for 1 Oct. at 19 : 13 UT and 19 : 32 UT). These spike flares had durations of only 10 and 5 seconds respectively, and obviously with a 5 second time resolution it is difficult to say if these are real. It is however interesting to note that Cristaldi and Rodono (1970,

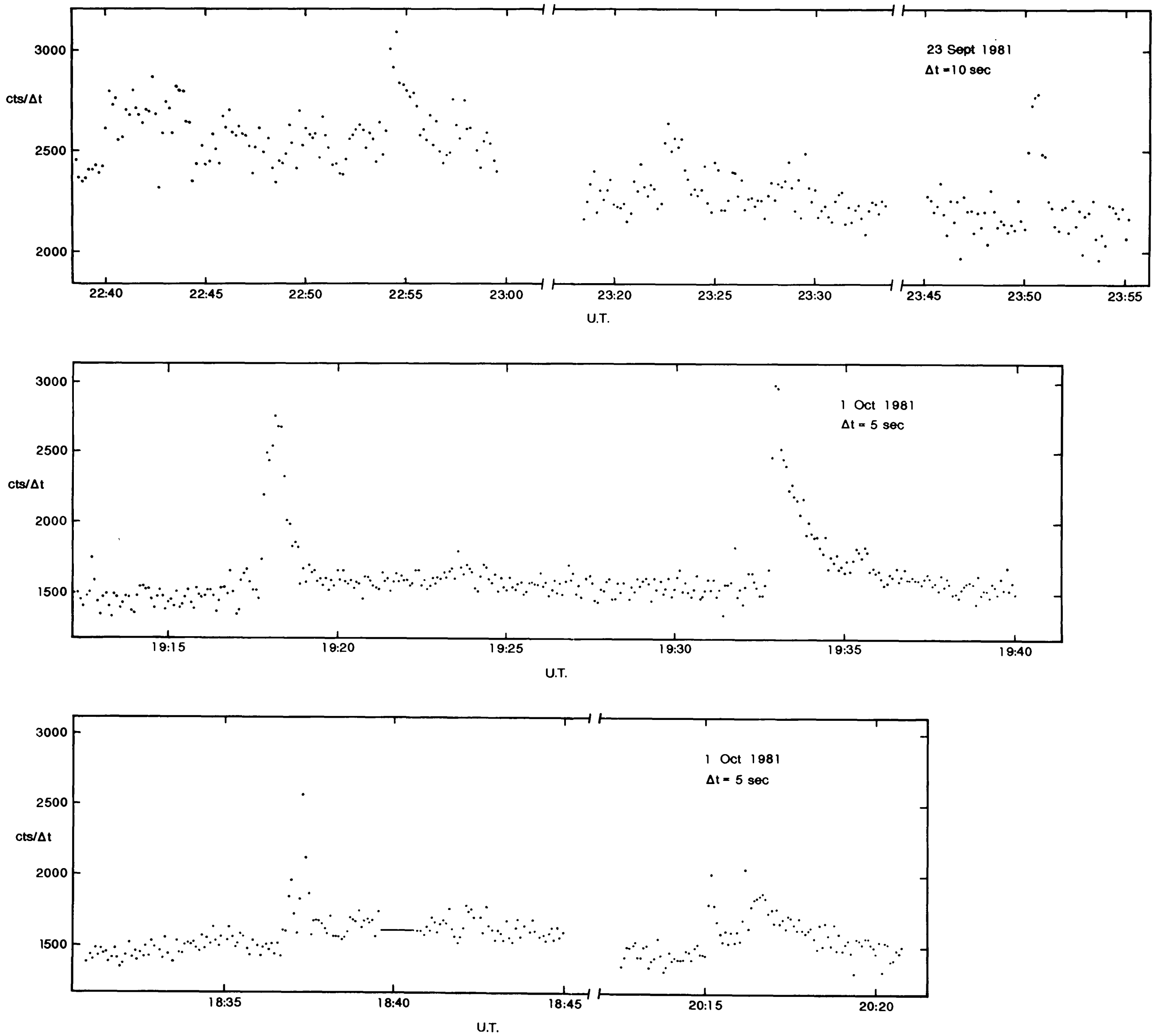

Fig. 1. The flares recorded on Gl 867B during the 23 September and the 1 October 1981 in counts/δt where δt is either 5 or 10 s

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1986A&A...156..283D

1973) observed the flare stars *UV* Cet and *EV* Lac with a time resolution of 0.5 seconds, detecting several short-lived events which had a decrease in brightness of a factor of six in only 4 or 5 s.

Calculation of the flare energies was carried out by first deriving the equivalent duration P_U (Gershberg, 1972), for each flare, i.e.

$$P_U = \Sigma_f[(I_{f+0} - I_0)/I_0]\,\Delta t$$

where I_0 is the pre-flare intensity, I_{f+0} the flare plus pre-flare intensity and Δt the integration time. The flare energy was then calculated by multiplying the equivalent duration by the quiescent luminosity, L_U, in the U-band. A value for L_U was derived by interpolating the data in Moffett's (1974) Tables 2 and 16, which yielded for the magnitudes in Table 5 and distance of 9.9 pc Gliese (1969), $L_U = 7.7\,10^{28}\,\mathrm{erg\,s^{-1}}$. The equivalent durations and flare energies can be found in Table 3. The time-averaged flare energy over the period of our observations in the Johnson U-band is therefore $L_U^* = 1.33\,10^{27}\,\mathrm{erg\,s^{-1}}$. This compares with values of $1.32\,10^{27}\,\mathrm{erg\,s^{-1}}$ and $1.18\,10^{27}\,\mathrm{erg\,s^{-1}}$ in 1977 and 1978 respectively, which would give a mean time-average flare energy of $1.29\,10^{27}\,\mathrm{erg\,s^{-1}}$. However, in the calculations of Byrne and McFarland (1980) and Byrne (1979) for the '77 and '78 observations, the 'quiescent' luminosity of Gl 867B was taken to be $5.5\,10^{28}\,\mathrm{erg\,s^{-1}}$. This difference is partially due to the slightly different U magnitude, although not entirely. Using the U magnitude given by Byrne and McFarland (1980) we derive $L_U = 6.7\,10^{28}\,\mathrm{erg\,s^{-1}}$ and therefore using this value for the '77 and '78 flares we derive a mean time-average flare energy over the three seasons of $1.46\,10^{27}\,\mathrm{erg\,s^{-1}}$.

Lacy et al. (1976) showed that a relationship exists between L_U^* and L_U. This work has been subsequently added to (and amended) by Byrne et al. (1984b) and Doyle and Byrne (1985). The most recent compilation included some 22 stars of both the active and inactive type. However, a more meaningful compilation would be L_U^* versus $L_{\rm bol}$ (the bolometric luminosity). For the twenty-two stars tabulated by Doyle and Byrne (1985), we derived bolometric luminosities in several ways and then took a mean of the results. These were from, i) the tabulation of $L_{\rm bol}$ by Pettersen (1980), ii) the relationships between $(V-R)$ and $R/R_\odot$, and $T_{\rm eff}$ given by Byrne et al. (1985), and iii) from the bolometric correction in terms of M_V from Pettersen (1983) and

$$M_{\rm bol} = 4.72 - 2.5\log(L/L_\odot)$$

from Allen (1973). The resulting values of $L_{\rm bol}$ and L_U^* are given in Table 4, with a plot of these parameters in Fig. 2. In this figure we see that the distribution of stars has to an upper limit (represented by the straight line) over four orders of magnitude in flare energy. The lower mass stars, such as CN Leo, emit less than $10^{-4.7}\,L_{\rm bol}\,\mathrm{erg\,s^{-1}}$ in flares, while more massive stars such as YY Gem emit less than $10^{-3.6}\,L_{\rm bol}$. To estimate the proportion of $L_{\rm bol}$ to that emitted in flares over the entire electro-magnetic spectrum, we must determine the ratio of L_U^* to $L_{\rm total}^*$ for stellar flares. Present data does not allow us to do this with any degree of certainty, but if we take the estimate of $L_{\rm total}^* = 14L_U^*$ given by Doyle and Butler (1985), we arrive at an upper limit of $10^{-3.6}$ $L_{\rm bol}$ for low mass flare stars and $10_{\rm bol}^{-2.5}$ for the higher mass flare stars. In this case the proportion of $L_{\rm bol}$ that is emitted in flares would be less than 1% for all dMe stars.

Doyle and Butler (1985) have shown that a very good correlation exists between the parameter, L_U^*, and the quiescent X-ray luminosity. From the time-averaged flare energy given in Table 4 for Gl 867 A and B, we derive from the relationship given by Doyle and Butler (1985) X-ray luminosities of $1.3\,10^{28}\,\mathrm{erg\,s^{-1}}$ and $5.0\,10^{28}\,\mathrm{erg\,s^{-1}}$ respectively, which gives a total luminosity of $6.3\,10^{28}\,\mathrm{erg\,s^{-1}}$ for the system. This is to be compared with the observed value of $1\,10^{29}\,\mathrm{erg\,s^{-1}}$ (Golub 1983).

Table 3. Dates and times of the flares recorded, plus their equivalent duration P_U and energy E_U. Flares with $P_U < 5$ s are doubtful

Date	U.T.	P_U (sec.)	E_U (10^{29} ergs.)
1981 23/34 Sept	~22:40	61.5	47.4
	~22:54	24.4	18.8
	~23:23	25.4	19.6
	~23:50	25.8	19.9
1/2 Oct	18:36:50	6.1	4.7
	18:37:15	10.2	7.9
	18:38	49.5	38.1
	19:12:50	1.6	1.3
	19:16:50	0.8	0.6
	19:17:20	2.9	2.3
	19:18:00	47.4	36.5
	19:19	36.2	27.9
	19:31:40	1.1	0.9
	19:32:00	1.0	0.8
	~19:33	69.3	53.3
	20:15	38.5	29.6

Table 4. The time-averaged flare energy in the Johnson U-band (L_U^*) and the bolometric luminosity ($L_{\rm bol}$) for twenty-two flare stars

Star name	Other name	Log L_U^*	Log $L_{\rm bol}$
Gl 15 A	—	26.0	32.0
UV Cet	Gl 65 AB	26.7	30.8
Gl 166 C	40 Eri C	26.8	31.4
Gl 182	V 1005 Ori	28.8	32.2
Gl 229	HD 42581	25.6	32.3
Gl 234 AB	V 577 Mon	26.8	31.4
YY Gem	Gl 278 C	28.9	32.5
YZ CMi	Gl 285	27.5	31.6
AD Leo	Gl 388	27.7	31.9
CN Leo	Gl 406	25.8	30.5
Gl 473 AB	Wolf 424 AB	26.3	30.9
Prox Cen	Gl 551	25.5	30.8
Gl 644	V 1054 Oph	27.7	31.9
Gl 735	V 1285 Aql	26.4	32.2
AT Mic	Gl 799	27.9	31.8
AU Mic	Gl 803	28.6	32.4
Gl 812	—	25.9	31.9
Gl 825	—	25.8	32.4
Gl 867 A	FK Aqr	27.7	32.2
Gl 867 B	—	27.1	31.6
EV Lac	Gl 873	27.2	31.7
EQ Peg	Gl 896 AB	27.8	31.9

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1986A&A...156..283D

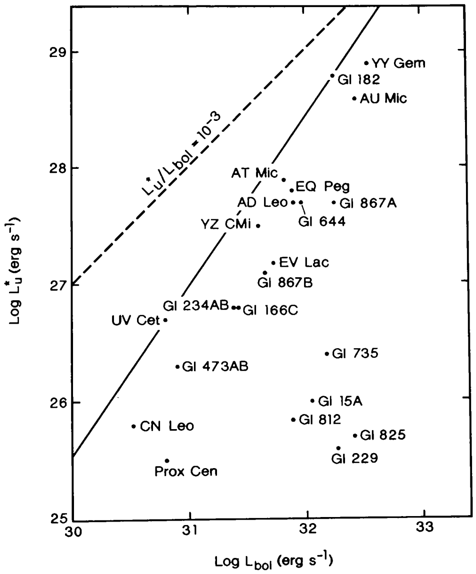

Fig. 2. A compilation of the time-averaged flare energy (L_U^*) in erg s^{-1} versus the bolometric luminosity (L_{bol}) in erg s^{-1}. The line of constant $L_U^*/L_{bol} = 10^{-3}$ (dashed) and the upper activity limit boundary (continuous line) are shown

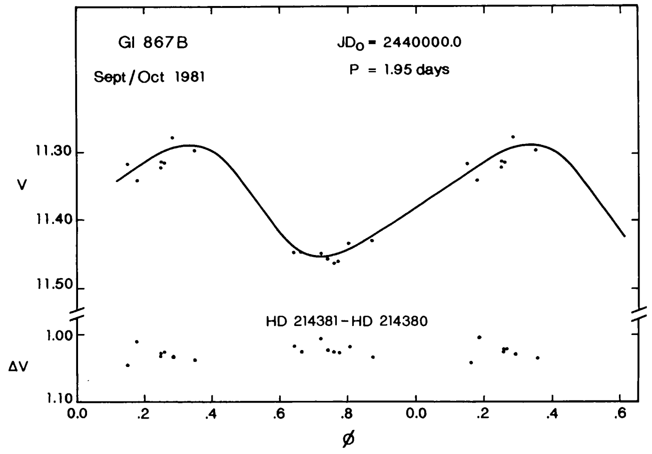

Fig. 3. V magnitude versus phase for Gl 867 B during September/October 1981. The assumed period is 1.95 d with $JD_0 = 2440000.00$. The difference between the V magnitude of the two comparison stars is shown

3.2. *BY-Draconis type variability*

Gl 867 B was differenced with respect to the two comparison stars, using the magnitudes as given by Byrne and McFarland (1980). There is good internal agreement between the resulting magnitudes amounting to no more than 0.005 magnitude in V. We therefore adopted a mean of the magnitudes derived differencing with respect to each star individually. These mean magnitudes are given in Table 5. From Table 5 we see that Gl 867 B is varying by approximately 0.15 in V with about a 2 day period. A series of light curves were generated, phases with respect to periods in the range 1.9–2.1 days. The best curve judged by eye appeared to be 1.95 d. but this period is poorly defined due to there being only one observation per night. As a check on our photometry we difference the two comparison stars, but found no systematic variation (see Fig. 3). The V magnitudes for Gl 867 B are plotted in Fig. 3, assuming the period of 1.95 d. This is the first time (to our knowledge) that a periodic variation has been observed in Gl 867 B. Byrne and McFarland measured Gl 867 B on 7 nights in 1978 but did not observe any variability with an amplitude $\Delta V > 0.01$. It is interesting to note that the flare activity observed on the 23 Sept and the 1 Oct 1981 occurred

Table 5. Photometric data for Gl 867 B, a mean of two observations per night (separated by approximately 20–30 mins.). Data was difference with respect to HD 214380 assuming $V = 9.18$, $(B-V) = +0.53$ and $(U-B) = +0.02$, and HD 214381 assuming $V = 10.20$, $(B-V) = +0.59$ and $(U-B) = +0.10$

Date	J.D.	V	$(B-V)$	$(U-B)$
1981 23/24 Sept	2444870.40	11.450	1.689	0.88
24/25 Sept	4871.40	11.322	1.660	0.88
25/26 Sept	4872.38	11.451	1.689	0.91
28/29 Sept	4875.48	11.326	1.684	0.89
29/30 Sept	4876.44	11.461	1.670	0.87
30 Sept/1 Oct	4877.44	11.317	1.675	0.92
1/2 Oct	4878.46	11.464	1.691	0.84
2/3 Oct	4879.25	11.345	1.677[a]	0.91
3/4 Oct	4880.30	11.453	1.686	0.95
4/5 Oct	4881.35	11.318	1.677	0.96
5/6 Oct	4882.41	11.437	1.691	0.99
7/8 Oct	4884.29	11.463	1.687	0.96
10/11 Oct	4887.27	11.283	1.673	0.94
11/12 Oct	4888.39	11.434	1.708[a]	0.93
12/13 Oct	4889.33	11.300	1.673	1.01

[a] second measurement of Gl 867 B in the B-band is suspect, only first measurement used

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1986A&A...156..283D

at spot maximum. However, since we did not observe Gl 867 B on any other night, it is not possible to discuss the significance of this result.

A parameter that appears to be related to the rotation period is the ratio of the soft X-ray luminosity to the bolometric luminosity (Walter 1982, Stern and Skumanich 1983, Byrne et al., 1984b). From the plot by Byrne et al., of log $L_x/L_{\rm bol}$ versus log P for dwarf K and M stars, we derive for a period of 1.95 d, $\log L_x/L_{\rm bol} = -3.0$. Thus, using the bolometric luminosity in Table 4, we derive an X-ray luminosity of $4.7\,10^{28}\,{\rm erg\,s^{-1}}$ for Gl 867 B which is consistent with the observed value for the whole system (i.e. $L_x = 1\,10^{29}\,{\rm erg\,s^{-1}}$).

3.3. UV spectra

The flux at the Earth for the lines observed in the spectra (N V, C IV and Mg h & k) are given in Table 6. The deflections in the spectrum due to C IV and N V were very weak, thus these fluxes are probably upper limits. For comparison with other late-type stars it is necessary to convert to surface flux. In this, we used the parallax as given by Gliese (1969) and the radius as determined by Pettersen (1980) from $(V-R)$. The surface fluxes for the above lines is also given in Table 6. Substantial flare activity was observed (see Fig. 1) during the IUE image SWP 15148 B. However, only a marginal increase was observed in the strongest lines in the spectra, i.e. N V and C IV, all other lines were weak or absent. For the long-wavelength spectra a flare occurred during the last minute of the 20 minute exposure, however, averaged over the total exposure time, this would not be expected to give rise to any detectable enhancements in Mg II. Therefore we expect the flux to be representative of the 'quiescent' state.

It has been shown (Catalano and Marilli 1983, Noyes et al., 1984) that a correlation exists between the mean level of Ca II H & K emission and the rotational period. Hartmann et al. (1984) has extended this to Mg II h & k. When expressed as the ratio of chromospheric flux to bolometric flux, $R_{\rm hk}$, the Mg II emission was shown to be well correlated with the parameter P/τ_c, where τ_c is a theoretically derived convective overturn time depending on $(B-V)$ and P (the observed rotation period). Hartmann et al., considered mostly G and K dwarfs, but this has now been extended to include M dwarfs (Doyle 1985). Taking the radius given above for Gl 867 B and the Mg II h & k flux given in Table 6, we derive from the effective temperature given in Pettersen (1980), $\log R_{\rm hk} = -3.8$. This implies from the extended data of Hartmann et al., $\log(\tau_c/P) = 1.1 \pm 0.1$ (Doyle 1985). Then taking τ_c from Noyes et al. (1984) for $(B-V) = 1.68$, we derive $p = 2.27 \pm (0.5)$ d, in agreement with the observed value of 1.95 d.

4. Conclusions

The time-averaged flare energy derived for the three seasons, 1977, 1978 and 1981 is very similar, despite the rather small number of hours of flare monitoring. This implies that Gl 867 B has maintained a reasonable 'constant' level of activity over several years. We have found Gl 867 B to be variable with a period of 1.95 days which if interpreted as due to rotational modulation is consistent with the observed X-ray flux for the Gl 867 system and is also in agreement with a correlation of period versus the ratio of Mg II h & k flux to bolometric flux. In view of (i) the relatively small number of late-type dwarfs (approximately 15) with established rotation periods and (ii) the accepted rotation-activity connection, it is important that the BY Draconis variability of this star is confirmed.

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Table 6. Integrated fluxes in spectral lines from the three IUE exposures. The SWP flares are probably upper limits due to low signal-to-noise ratio spectra

	Line flux at the earth ($10^{-13}\,{\rm erg\,cm^{-2}\,s^{-1}}$)			Surface flux ($10^{5}\,{\rm erg\,cm^{-2}\,s^{-1}}$)		
	N V 1240	C IV 1550	Mg h and k 2800	N V	C IV	Mg h and k
SWP 15148 A	0.8	0.6		1.0	0.8	
SWP 15148 B	1.0	1.6		1.3	2.0	
SWP 15149	1.7	0.9		2.2	1.2	
LWR 11653			6.1			7.8

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1986A&A...156..283D

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