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SOME EVIDENCE ON THE EVOLUTION OF THE FLARE MECHANISM IN DWARF STARS

ANDREW SKUMANICH
High Altitude Observatory, National Center for Atmospheric Research[1]
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ABSTRACT

White-light flare parameters are estimated for the Sun as a star. It is found that these parameters fall in the same domain as those for the dMe flare stars. In particular, it is found that the time-averaged flare power loss and quiescent coronal soft X-ray power loss at solar maximum satisfies the recently proposed flare power-coronal X-ray relation for dMe stars (Doyle and Butler; Skumanich). In addition, one finds that dM stars, which are believed to be magnetically evolved dMe stars, also satisfy the same relation. On this basis, an evolutionary scenario is suggested for the flare mechanism in which the total flare rate remains, more or less, constant but the mean flare yield decreases linearly with coronal X-ray strength. It is also suggested that the flare mechanism is universal in all magnetically active dwarfs.

Subject headings: stars: coronae — stars: flare — stars: late-type — stars: magnetic — Sun: flares

I. INTRODUCTION

In a paper presented at the recent Giovanelli colloquium (Skumanich 1985), the author suggested that the flare mechanism in dwarf stars operates on a large[2] (flare) and small (microflare) scale and that microflares energize the "quiescent" X-ray coronae. This was based on the observation of a correlation between white-light flare properties for dMe stars (the "e" designates the presence of quiescent Balmer emission lines) and their *quiet* coronal X-ray strength. In particular, it was found that the time-averaged (mean) U-band (315–385 nm) flare power, $\dot{Y}_U$, was in *constant* proportion ($= 0.04$) to the quiescent coronal soft X-ray power loss, L_{XR}. In other words, the mean flare power loss correlated *linearly* with the coronal X-ray power loss over three orders of magnitude. A similar correlation was obtained independently by Doyle and Butler (1985) and Whitehouse (1985). In addition, it was also argued that the mean optical (or U-band) flare rate, $\dot{n}$, varied inversely with L_{XR}, namely, as $(L_{XR})^{-2/3}$. Thus the flare mechanism appears to have the property that high flaring rates are associated with low (mean) flare yields,[3] Y_U. The extrapolation of such a mechanism by Skumanich to power the "quiet" coronae of these stars appears to be confirmed by recent observations of frequent low-yield soft X-ray microflares on dMe stars (Butler and Rodonò 1985) as well as on the Sun (Schadee, DeJager, and Svestka 1983). It should also be noted that hard X-ray microflares have been detected for the Sun (Lin *et al.* 1984).

Finally, it was suggested that the dMe stars which make up the correlation are in a "saturated (magnetic) activity" state. For *such* stars of any mass, their coronal X-ray power loss is a constant fraction of the luminosity of the star (Rucinski 1984). As we shall see below, the correlation line for such "saturated" stars forms a mass, or $(R-I)$ color sequence, from the weakest X-ray emitter, GLS 406 [$(R-I)_K = 1^m.84$, $L_{XR} = 0.93 \times 10^{27}$ ergs s^{-1}] to the strongest, GLS 278Cab[4] [$(R-I)_K = 0^m.78$, $L_{XR} = 3.40 \times 10^{29}$ ergs s^{-1}]. This presumably reflects the dependence of the flare mechanism in the "saturated" state with location on the main sequence. With evolutionary changes in the dynamo "mechanism," i.e., in the associated magnetic fields and rotational (and/or shear) helicity, one may expect changes in the flare rate and yield even though convective zone (CZ) properties, such as thickness and turbulent velocities, may stay essentially fixed. We have in mind a secular decay from the saturated state by a self-regulating magnetized-wind braking mechanism as is envisioned in the G dwarfs (see Skumanich and Eddy 1981).

The question of the secular *evolution* of the flare parameters, $\dot{n}$, Y_U, and $\dot{Y}_U$ as a function of $L_{XR}(t)$ is of considerable interest. Here we propose to use the coronal X-ray luminosity as a proxy for the total closed magnetic flux at any particular epoch (Golub *et al.* 1982; see also Vaiana 1983). The purpose of this paper then is to explore this evolutionary question with extant flare data for both M dwarfs *without* Balmer emission lines, i.e., for magnetically evolved M dwarfs, as well as for other spectral types, in particular, the Sun (G2V) and V471 Tau A (dK2). The use of other spectral types allows one to check on the "universality" of the flare mechanism along the main sequence.

II. ANALYSIS

The issue of the uniqueness of observational flare parameters and the role of detection thresholds and completeness must be understood before one compares heterogeneous data. If $\dot{n}(E)$ is the cumulative rate of flares with yields greater than or equal to E ergs, then one can easily show that the (time) average power loss, $\dot{Y}$, by such flares is given by

$$\dot{Y}(E, E^c) = \dot{n}(E)E + \int_{\ln E}^{\ln E^c} \dot{n}(E')E' d \ln E' \tag{1a}$$

$$= \dot{n}(E)E\left\{1 + \int_{\ln E}^{\ln E_c} \left[\frac{\dot{n}(E')E'}{\dot{n}(E)E}\right] d \ln E'\right\} \tag{1b}$$

$$= \dot{n}(E)Y(E, E_c) . \tag{1c}$$

We assume here that there is a sharp cutoff to flare yields at $E = E_c$, i.e., that $\dot{n}(E)E = 0$ for $E > E_c$, and that $\dot{n}(E_c)E_c =$

[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation.
[2] High energy but low frequency.
[3] Note that $\dot{Y}_U = \dot{n}Y_U$, hence $Y_U \approx (L_{XR})^{5/3}$.
[4] The "ab" designation indicates that component C is a spectroscopic binary. Colors are on the Kron system.

constant ($\neq 0$) which represents a characteristic property of the flare mechanism. The mean flare yield is defined by equations (1b) and (1c). The form $\dot{n} \times E$ is used in equation (1a) because it is a slowly varying function of E; see below. We view E_C as the maximum yield a coronal loop can support without blowing itself apart and thus quenching optical conversion (Gibson 1985).

There is some uncertainty as to the value of the lower limit E that is to be used. In practice the detection threshold, E_d, of the observing system (telescope and detector) fixes the value of E. This leads to the difficulty that if a single telescope is used, E_d, and hence $\dot{Y}$, $\dot{n}$, and Y may vary from star to star for purely instrumental reasons. If data sampling is *complete* enough so that the estimate of the cutoff energy, E_c, is well defined then one could consider selecting E at some fixed fraction of E_c, viz., $E \equiv E_r = E_c/r$. In the case of the data of Moffett (1974, hereafter M74; see also Lacy, Moffett, and Evans 1976, hereafter LME 76), a variety of telescopes were used with one and the same detector system such that the choice $r = 100$ ($= 2$ dex) encompasses most of the target stars; i.e., for these stars one finds that $E_d \approx E_{100}$. It is for this reason that Skumanich (1985) restricted his attention mostly to the M74 and LME 76 data. However, for a few stars E_d/E_c was $\frac{1}{2}$ to 1 dex larger (r smaller). Note that errors in the estimate of E_c, as well as differences in threshold, E_d, give rise to "uncertainties" in r.

We can estimate the effect of a $\frac{1}{2}$ or 1 dex uncertainty in r on the flare parameters if we use the current evidence that $\dot{n}(E)$ can be approximated by a power law; i.e., $\dot{n}(E) \approx \dot{n}(E_c) \times (E_c/E)^{\beta}$ with $0(\beta) \approx 1$ (Kunkel 1973, hereafter K73; LME 76; Pettersen, Coleman, and Evans 1984, hereafter PCE 84; Walker 1981, hereafter W81). Actually, β appears to fall in the range of 1.0–0.6 and may vary systematically with L_V (e.g., PCE 84) and, hence, with L_{XR}.[5] However, other authors (W81; LME 76) have found dissimilar β's for stars with similar coronae which casts some doubt about the systematic variation.

With a power-law spectrum one can represent equation (1), for 3 dex $\geq r \geq 1$ dex, by the following monomial $\dot{Y} = \dot{Y}(E_r = E_c/r, E_c) \approx a(\beta)r^{b(\beta)} \times \dot{n}(E_c)E_c$ with the coefficients $(a, b) = (2.5, 1/6)$ for $\beta = 1.0$ and $(1.75, 1/20)$ for $\beta = 0.6$. Thus the dependence of $\dot{Y}$ on $\dot{n}(E_c)E_c$ is fairly insensitive to r. This insensitivity is confirmed by the fact that one not only finds a $(\dot{Y}_U, L_{XR})$ correlation with flare data from a single data source with its characteristic r (Skumanich 1985) but also with a variety of sources (Doyle and Butler 1985).

In the case of the "total" (cumulative) flare rate, $\dot{n} = \dot{n}(E_r) \approx r^{\beta} \times \dot{n}(E_c)$ so that one must exercise care in comparing heterogeneous data. In the case of the LME 76 data one finds, on the average, that $\langle\beta\rangle \approx 0.8$, so that differences of a factor of 3 may occur for a $\frac{1}{2}$ dex variation in r. One should note that incompleteness and threshold "errors" may conspire to produce partially cancelling effects, for instance, in the case of GLS 388 below.

The dMe, or "activity-saturated" stars discussed by Skumanich (1985) are listed in Table 1 by order of $(R-I)_K$ and are identified by the LME 76 source designation in column (8), except for GLS 867, which was included from the data of Byrne and McFarland (1980, hereafter BM 80). The column (1) gives the star number in the Gliese (1969) catalog. The column (3)

[5] The current tendency to correlate flare parameters with L_U, (or L_V) the U-luminosity (or visual) of the star needs to be reexamined in light of the flare-loss vs. coronal X-ray loss correlation.

TABLE 1

PARAMETERS FOR FLARE STARS

Gliese (1)	Other (2)	$(R-I)_K$ (3)	L_{XR} (10^{27} ergs s^{-1}) (4)	$\dot{Y}_U$ (10^{27} ergs s^{-1}) (5)	$\dot{n}$ (10^{-4} s) (6)	Y_U (10^{30} ergs) (7)	N (8)	Source (9)	$t_{1/2}$ (s) (10)
"Saturated" Flare Stars									
406	CN Leo	1.85	0.93 BK	0.029	9.5	0.03	112	LME 76	9
65AB	UV Cet	1.68	3.0 J	0.12	4.6	0.26	114	LME 76	11
473AB	Wolf 424	1.62	5.0 BK	0.19	11.5	0.20	11	LME 76	...
285	YZ Cmi	1.35	34 J	0.87	3.2	2.8	64	LME 76	29
669B	...	1.18	23 HJ	...	2.4	...	0	M74	...
873	EV Lac	1.17	40 AW	1.6	0.91	17	22	LME 76	...
896AB	...	1.13	60 J	2.4	2.1	11.5	58	LME 76	...
896B	EQ Peg	1.42	(10) ...	...	1.3	...	...	R78	...
896A	...	1.20	(60) ...	...	0.8	...	...	R78	...
388	AD Leo	1.12	100 J	0.46	1.2	4.0	9	LME 76	...
388	AD Leo	1.12	100 J	5.7	1.0	52	85	PCE 84	41
644A(Bab)	Wolf 630	1.08	200 J	...	0.45	...	0	M74	...
867Aab	FK Agr	0.94	200 BK(AB)	5.6:	0.65:	85:	5	BM80	...
815AB	...	0.91	(100) ...	...	0.65	...	0	M74	...
616.2	CR Dra	0.90	130 J	...	0.18	...	0	M74	...
278Cab	TT Gem	0.78	340 J	52	0.44	1200	19	LME 76	...
719AB	BY Dra	0.54	320 J	...	0.24	...	0	M74	...
"Evolved"/Other Flare Stars									
551	Proxima Cen	1.65	1.1 BK	0.036	3.4	0.11	34	W81	13.6
447	FI Vir	1.30	0.47 BK	...	(0.05)	3.8	1	LH72	90
15A	GX And	0.88	1.3 BK	0.096	0.58	1.65	10	PG80	45
229	...	0.82	1.1 BK	0.13	0.83	1.62	2	K73	102
825	...	0.69	1.9 BK	0.095	0.1	8.9	1	B81	48
... .	V471 Tau A	0.4	280 Y	...	(0.67)	150	2	Y83	57
... .	Sun	0.215	1.6 AL	0.02	0.18	1.1	...	...	200

gives the soft X-ray luminosity from Ambruster, Snyder, and Wood (1984, hereafter AW); Ayres, Marstad, and Linsky (1981, hereafter AL); Bookbinder *et al.* (1985, hereafter BK); Harris and Johnson (1985, hereafter HJ); Johnson (1983, hereafter J), and Young *et al.* (1983, hereafter Y). Values listed in parenthesis were obtained from the $L_{XR}(L_U)$ correlation for saturated dMe stars. The columns (4)–(6) give the flare parameters $\dot{Y}_U(E_d)$, $\dot{n}(E_d)$, and $Y_U(E_d)$, respectively; here, U designates U-band photometry. Column (7) gives the total number of flares, N. The partition of total system (AB) flares between GLS 896A and GLS 896B is based on the fractional partition observed by Rodonò (1978, hereafter R78).

The effect of incompleteness is illustrated by the second data set listed for GLS 388. This data set, PCE 84, was obtained with the same observational system as the LME 76 set. The value for E_c was found to be 4.1×10^{32} ergs, a factor of 10 higher than for LME 76. In estimating flare parameters from the PCE 84 data a value of $r = 2$ dex was used rather than the PEC 84 value of 2.5 dex ($E_d = 10^{-2.5}E_c$) in order to be consistent with the LME 76 parameters.

Not all dMe stars are necessarily "activity saturated," i.e., necessarily magnetically young.[6] A case in point is Proxima Cen (GLS 551) which W81 finds to be less flare active than other dMe stars of similar $(R-I)$ color, e.g., UV Ceti. This is consistent with the fact that the quiescent soft X-ray luminosity is lower than that predicted from the $L_{XR}(L_U)$ relation for the "saturated" dMe stars. Note, however, that this star is not as magnetically evolved as would be expected from the solarlike age of α Cen A, its primary companion. I estimate the flare parameters for GLS 551 from W81 data using $r = 2$ dex, for consistency with LME 76, and $\beta = 0.7$. The resulting values[7] are listed in Table 1. The question of whether there are other "partially" evolved dMe stars has yet to be explored.

Among the 17 dM stars whose soft X-ray luminosities are known, only GLS 15A (Pettersen and Griffin 1980, hereafter PG80), GLS 229 (K73) and GLS 825 (Byrne 1981, hereafter B81) have adequate observations to allow one to estimate flare parameters. Because of the small number of detected flares I have used the estimators, $\dot{Y} = \sum Y_i/T$, $\dot{n} = n/T$, and $Y = \sum Y_i/n$, where T is the observing interval. I list GLS 447 even though only the yield could be estimated from the data of Lee and Hoxie (1972, hereafter LH72).

Finally, we consider two flare stars with significantly different spectral types, viz., V471 Tau A (dK2) and the Sun (G2V). The case for V471 Tau A is the same as GLS 447; I determined the average yield from the data of Young *et al.* (1983) using a corrected calibration for the U-band luminosity of the dK2 star, viz., $L_U = 2.22 \times 10^{31}$ ergs s^{-1}. For both V471 and GLS 447 the flare rates listed in Table 1 were estimated from $\dot{Y}_U$ derived from Figure 1 and the observed coronal X-ray luminosity of these stars.

Except for the ACRIM data, which is overly broad band for the blue continuum characteristic of flares, there is no "Sun as a star" measurement that allows one to directly estimate solar optical flare parameters. The frequency of solar Hα flares at solar maximum is well documented (Smith and Smith 1963)

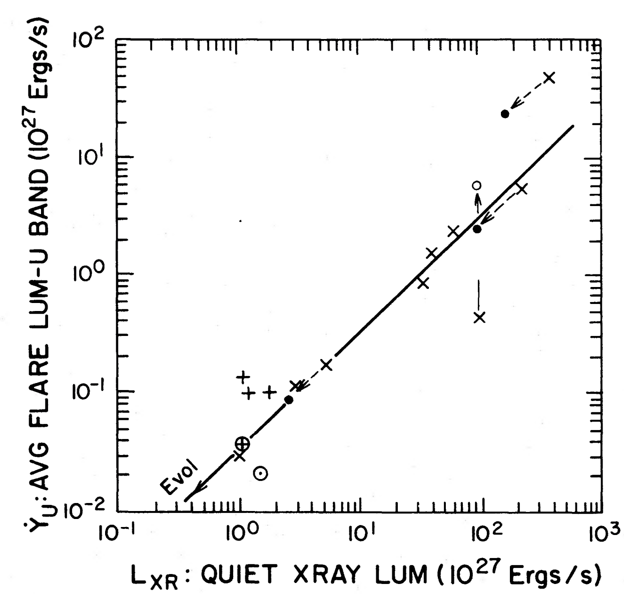

FIG. 1.—Regression of average U-band power loss, $\dot{Y}_U$, with quiet coronal X-ray power loss, L_{XR}. Saturated dMe stars are indicated by a cross (×), estimated single-star values (filled dots) are pointed to by arrows; see Skumanich (1985). Magnetically evolved dM stars are indicated by plus signs (+); GLS 551 is indicated by ⊕; and the Sun is indicated by ⊙. GLS 388 is indicated by its LME value, "×", and by its PCE value (*open circle*). (Reproduction from Skumanich (1985), courtesy *Australian Journal of Physics*.)

with an average rate of $\dot{n}(\mathrm{H}\alpha) = 1.0 \times 10^{-4}$ s^{-1} (for three solar maxima). However, not all Hα flares have detectable white-light emission. In a statistical study of the spectra of 60 Hα flares, Michard (1959) found that 11 had detectable optical or "white-light" continuum. Assuming that the threshold here is appropriate for comparison with the stellar flare data, then the continuum flaring rate is $\dot{n} = (11/60) \times \dot{n}(\mathrm{H}\alpha) = 0.18 \times 10^{-4}$ s^{-1} (see Cristaldi and Rodonò 1975, hereafter CR75). I note that this value is a factor of $\sim$40 larger than that given for white-light flares by Neidig and Cliver (1983). However, their rate applies to flares whose associated Soft X-ray yields fall in the X-ray class >M4, i.e., to high energy flares. More typical yields are at least a factor of 10 smaller and one would expect a concommitant factor of 10 increase (for $\beta = 1$) in the continuum flare rate. This suggests that our estimate is quite reasonable but may be a factor of 4 on the high side.

To estimate the mean flare yield in the U-band I extend the argument of Kahler and Shulman (1972). They argue that the white-light yield of solar flares can be estimated from the observed mean ratio of (Y_{EUV}/Y_{XR}) for solar flares (Donnelly 1971) and the observation of a close correspondence between white-light (3500–6500 Å) flares and extreme ultraviolet (EUV, 10–1030 Å) enhancements (McIntosh and Donnelly 1972). Kahler and Shulman suggest that $Y_{WL} = 17 Y_{XR}$ (0.6–1.5 keV). According to LME 76, one has that $Y_U = (1/2.4) Y_{WL}$, hence $Y_U = 7 Y_{XR}$. I estimate that the mean[8] X-ray yield for 45 solar flares during the *Skylab* period (Kahler 1978) is $Y_{XR} = 1.6 \times 10^{29}$ ergs (0.7–1.5 keV). Thus I find that $Y_U = 1.1 \times 10^{30}$ ergs. This is a factor of 2.7 dex *smaller* than the estimate of CR75 (after correction to Moffett's calibration) which is based on (a) continuum contrast (0.5), (b) flare size ($0.001\pi\, R_\odot^2$), and

[6] I note that stars may remain saturated and be kinematically old if they are in binary systems (SB's) where spin-orbit coupling may provide a continuous source of helicity for the maintenance of the dynamo in a saturated state; see Kunkel (1975) and Young, Sadjadi, and Harlan (1985).

[7] I note that the value of $\bar{L} = \dot{Y}_U(10^{26}, 10^{30})$ given in W81 appears to be in error. I find $\log \bar{L} = 25.61$.

[8] This average may be underestimated by as much as a factor of 2.5 to 5.0 since Kahler's events appear to be unrepresentative at the high-energy end (Kahler 1978, p. 98).

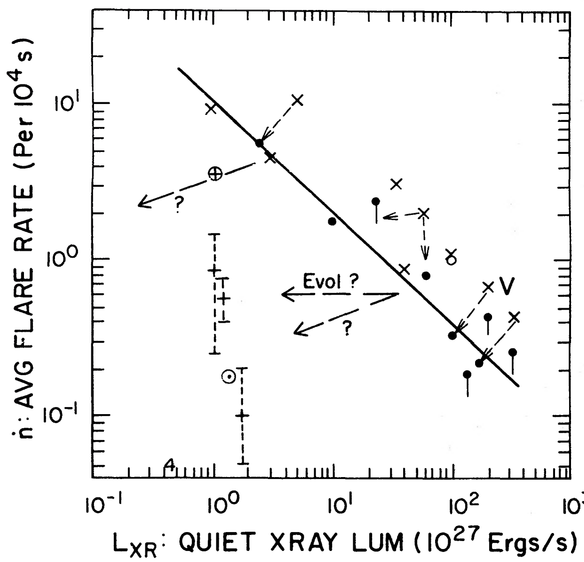

FIG. 2.—Regression of the average flare rate, $\dot{n}$, per 10^4 s with L_{XR}. Saturated dMe stars are indicated as in Fig. 1; in addition, upper limits are indicated by a filled dot with a vertical bar (♦); see Skumanich (1985). Magnetically evolved stars are indicated as in Fig. 1 but with error bars. Estimated rate for V471 Tau A is indicated by "V" and for GLS 447 by "4." (Reproduction from Skumanich (1985), courtesy *Australian Journals of Physics.*)

(c) flare duration (10 minutes). I believe my estimate is more trustworthy and appears to be consistent with yields reported by Hiei (1986) and by Gesztelyi (1986); see also Hiei (1982). Finally, I find for the flare power loss, $\dot{Y}_U = 0.18 \times 10^{-4}$ $s^{-1} \times 1.1 \times 10^{30}$ ergs $= 2.0 \times 10^{25}$ ergs s^{-1}.

In support of the above method of estimating the mean white-light yield for solar flares, I note that the simultaneous white-light and X-ray solar flare data listed by Rust (1986) yield a constant ratio of Y_{WL}/Y_{XR}, i.e., a *linear* relation as argued here (D. Neidig, private communication).

I compare the flare parameters for the dM stars, V471 Tau A, Proxima Cen (GLS 551), and the Sun with those for the emission line stars in Figures 1, 2, and 3, where the flare power loss, flare rate, and mean flare energy are compared to the coronal X-ray power loss.

The remarkable result apparent in Figure 1 is that the flare power loss in these stars appears to be consistent[9] with that predicted from the ($\dot{Y}_U$, L_{XR}) correlation for the emission stars. This result was already apparent in the plot of Doyle and Butler (1985), although they made no specific note of it. The fact that the Sun "fits" the relation suggests that the flare mechanism is "universal" for magnetically active main-sequence stars and that magnetic evolution is *downward* along the linear regression line (solid), i.e., $\dot{Y}_U(t) = 0.04L_{XR}(t)$. Proxima Centauri (GLS 551) has evolved "downward" from its color class as given by UV Cet (GLS 65AB).

A comparison of flare rates is given in Figure 2. It appears that the flare rates are approximately[10] the same as in the dMe stars at one and the same color class. The evidence from Proxima Cen (GLS 551), our best data point, would indicate that flare rates decrease weakly with evolution. If our solar estimate errs on the high side (see above) then the Sun would be more consistent with a weak decay. The most conservative hypothesis, given the paucity and quality of the data, is that the flare rate remains constant as the star evolves magnetically, i.e., as a function of $L_{XR}(t)$.

In Figure 3, I present a comparison of flare yields. Here the yields for the "evolved" stars also show a significant departure from their equivalent color class. If the flare rates remain constant then the yields would have to decrease linearly with $L_{XR}(t)$, to satisfy Figure 1, as indicated by the evolution line. The accurate data for Proxima Cen (GLS 551) supports such a scenario. If our solar estimate errs on the low side (see above) then, as in Figure 2, the Sun would "fit" more consistently. The flares on V471 Tau A would appear to corroborate the universality of the flare mechanism on dwarf stars. However, the V471 and GLS 447 flares may be somewhat atypical (see below).

In order to check on the representativeness of the flares in the "evolved" stars we consider their location in a regression of average flare half-life (time to fall from peak to half-peak), $t_{1/2}$, with $(R-I)_K$ color, as given in Figure 4. For completeness we have included several dMe stars in Figure 4 which are not listed in Table 1; these are from K73. The use of $(R-I)_K$ is more appropriate than the visual luminosity (see PCE 84) since it is a more accurate indicator of the radiating properties of the optical flare region and does not include a radius factor. The flares for the nonemission stars, except for GLS 447 and V471 Tau A, appear to agree with the correlation for the dMe stars. This agreement supports the contention made here that the flare mechanism, on average, has a universal character for all magnetically active dwarfs. The deviation of V471 Tau A and GLS 447 is within the range of variation in $t_{1/2}$ found for dMe stars (see K73); however, the observed flares are atypical. I note in passing that the source of the variation may be due to different kinds of driving instabilities that can produce a flare event.

In either the conduction front or particle beam scenarios for

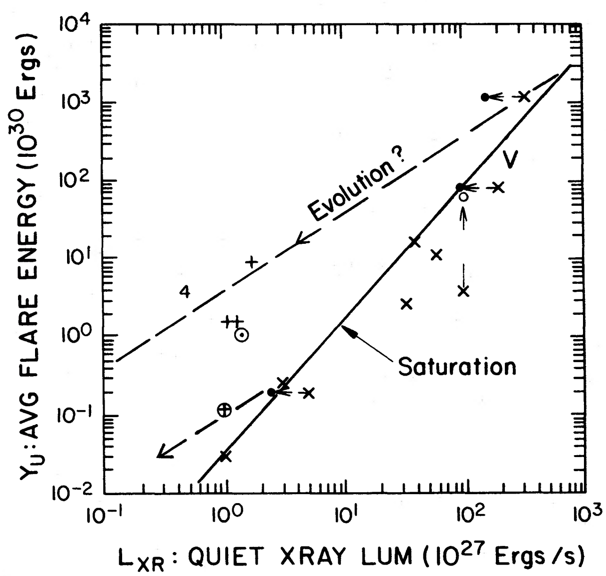

FIG. 3.—Regression of average flare yield, Y_U, with L_{XR}. Symbols as in Fig. 2. The secular evolution of the flare yield with $L_{XR}(t)$ is indicated by the dashed lines for two different colors (≈ 0.7, *upper*; ≈ 1.7, *lower*).

[9] A factor of 2 deviation is within the "discrepancy" I find when I compared the CR75 data with LME 76.

[10] Possible threshold or cutoff energy "uncertainties," or both, must be kept in mind here. For example, I found that the CR75 data appeared to be systematically 1.6 times lower than the LME 76 set, presumably because E_d is higher.

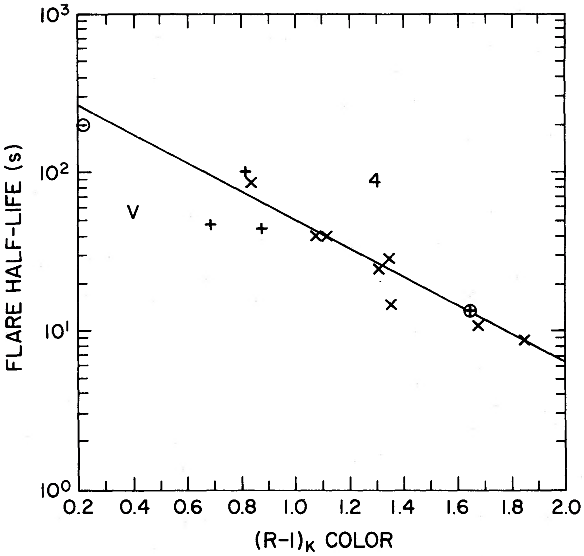

FIG. 4.—Regression of U-band flare half-life (time to fall from peak to half-peak), $t_{1/2}$, with photospheric temperature as parameterized by $(R-I)_K$ color. Symbols as in previous figures.

flare energy propagation into the lower atmosphere one expects that the radiating property of the region being excited, specifically the reradiation time, governs both the white-light flare rise time as well as the half-life. For a rapid enough energy release one expects both times to be, on the average, approximately equal, as appears to be the case in GLS 388 (AD Leo), PCE 84. It is quite possible for flare morphologies to be a function of the specific flare instability (D. M. Gibson, private communication) but we argue that the cooling history is not.

III. DISCUSSION

The idea that flares on the Sun are related to those on UV Ceti flare stars is not a new idea (see Kunkel 1970). However, this view is not accepted by many (see Gurzadyan 1980, pp. 326, 330). Our contention is that not only is there a common magnetic "driver" for flares and quiescent coronae, as shown by the (flare power, quiet coronal power) correlation but that the "driver" *is* universal among late-type dwarf stars. Further, we have presented evidence here for its evolutionary change with decaying magnetic activity.

As parametrized here the high-energy end of the "driver" spectrum is described by three parameters[11] ($\dot{n}_c$, E_c, β); all three play a role in our cumulants ($\dot{n}$, Y, $\dot{Y}$). If one uses the decay of coronal X-ray luminosity as a proxy for the decay of closed magnetic flux with age (see Golub *et al.* 1982) then the extant data suggests that the cumulative flaring rate remains constant or decreases weakly and that flare yields decrease appreciably with a decrease in the total closed magnetic flux. This implies that the spectral cutoff, E_c, for the driver shifts to lower energies. It is not clear whether this is with or without a significant change in hardness, i.e., in slope, β. Further speculation as to the nature of the flare mechanism implied by the proposed scenario must await significantly more data and a more careful analysis of the flare rate, $\dot{n}$, with due account for completeness and a careful treatment of threshold effects, E_r.

If one were to use the solar minimum state as representative of a more magnetically evolved state compared to solar maximum then the decrease in spot numbers would imply a significant decrease in the number of interacting active regions and hence in the cumulative flare rate. This is contrary to our suggested scenario. However, recent observations show that significant magnetic flux interaction continues to be present at solar minimum as indicated by the X-ray bright points (or XBP) whose number is 180° out of phase with sunspot number (Golub 1981). These observations suggest that flux interaction may occur on two different scales—spots versus XBPs. Since XBPs flare, they may keep the flare rate from falling appreciably from maximum to minimum. Whether the observed (average) Hα flare rate at solar minimum, $\dot{n}(\mathrm{H}\alpha)_{\min} \approx 0.08 \times 10^{-4}\ \mathrm{s}^{-1}$ (Smith and Smith 1963), includes XBPs flares is not known. I note that an additional factor of 6 contribution by XBPs to the minimum Hα rate would keep the white-light rate (presuming the same white-light fraction) at a level of $\sim 0.08 \times 10^{-4}\ \mathrm{s}^{-1}$, i.e., at only a factor of 2 below that at solar maximum. Since the estimated quiescent X-ray level at solar minimum is $L_{XR}(\mathrm{min}) = 0.58 \times 10^{27}\ \mathrm{erg\ s}^{-1}$ (Ayres *et al.* 1981) such a flare rate would be consistent with the proposed scenario.

With regard to V471 Tau A, it would appear that this star is not significantly evolved (magnetically). The star is a rapid rotator ($P \approx \frac{1}{2}$ day) tidally locked with a white dwarf companion. Illumination from the latter appears to drive enhanced chromospheric activity as shown by the change of the Hα line from a *diluted* state on the face away from the white dwarf to an emission state (above the continuum) on the face opposite the white dwarf (Skumanich and Young 1984). Hα dilution in a dK2 star implies strong chromospheric activity; in addition, this star exhibits "BY Dra" spottedness so that its "unevolved" state is not surprising.

Moffett (1985) suggests a different interpretation to the AD Leo data sets. It is possible, he argues, that flare stars have periods of high and low activity and that the two data sets represent just such a situation. If this were the case then the similar flare rate for the two states (see Fig. 2) would corroborate the scenario suggested here. The less active state would also have a lower flare power loss and lower yield, as is the case. To fit the correlations in Figures 1 and 3 the coronal power loss would have had to be $\sim 1.4 \times 10^{28}$ ergs s^{-1}, a factor of 7 lower at the earlier epoch than observed (at a later epoch). Such a suggestion can certainly be tested with future X-ray observations.

Finally, our evolutionary scenario presented here is consistent with the observations of flare stars in open clusters where, as one considers older and older clusters, the spectral type at which flares are visible shifts to the later spectral types (Haro 1975). This would be explained by a shift of Y_U (and hence $\dot{Y}_U \approx Y_U/t_{1/2}$) to lower and lower values so that the visibility of flares shifts to cooler stars.

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[11] For completeness we note that Kunkel's flare activity parameter, M_{U0} ($\equiv$ a characteristic *peak* flare power, in U-magnitudes), is related (approximately) to the parameters introduced here by the condition on E_0 that $\dot{n}(E = E_0, E_C) = 2.77 \times 10^{-4}\ \mathrm{s}^{-1}$ where $E_0(\mathrm{ergs}) = 3.65 \times 10^{34} \times 10^{-0.4 M_{U0}} \times 1.45 \times t_{1/2}$ (s). Thus, for Kunkel's $\beta = 1.0$ (K73), one finds from eq. (1) that M_{U0} is a logarithmic measure of $(\dot{n}_c E_c/t_{1/2})$. Kunkel's correlation of M_{U0} with M_V represents the (flare power, coronal power) correlation for saturated dMe stars.

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ANDREW SKUMANICH: National Center for Atmospheric Research, High Altitude Observatory, P.O. Box 3000, Boulder, CO 80307-0440