1989A&A...222..179V

Astron. Astrophys. 222, 179–186 (1989)

ASTRONOMY
AND
ASTROPHYSICS

IUE observations of the M dwarfs CM Draconis and Rossiter 137 B: magnetic activity at saturated levels*

O. Vilhu[1], **C.W. Ambruster**[2], **J.E. Neff**[3], **J.L. Linsky**[4], **A. Brandenburg**[1], **I.V. Ilyin**[5], and **N.I. Shakhovskaya**[5]

[1] Observatory and Astrophysics Laboratory, University of Helsinki, SF-00130 Helsinki, Finland
[2] Department of Astronomy, Villanova University, Villanova, PA 19085, USA
[3] Code 681, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[4] JILA, University of Colorado and NBS, Boulder, CO 80309-0440, USA
[5] Crimean Astrophysical Observatory, P/O Nauchny, 334413 Crimea, USSR

Received September 6, 1988; accepted March 31, 1989

Summary. We present IUE observations of two active M dwarfs, CM Draconis and Rossiter 137 B, that we expect to be almost totally convective. CM Dra was also monitored optically during the IUE observations, and two flares were detected. CM Dra is a binary star (M 4 + M 4, $P = 1.27$ d) and Rst 137 B (M 3 – 5) forms a physical pair with the rapidly rotating pre-main sequence K star AB Dor (HD 36705). The activity of CM Dra is due to the forced rotation in a close binary, while we suppose Rst 137 B to rotate fast enough (due to its young age) to generate its magnetic activity. We compare our results with other relevant data and determine the chromospheric-coronal saturation levels of cool dwarfs between $0.3 < B-V < 1.6$ [Eq. (1)]. Saturated F stars have stronger chromospheres than saturated M stars, but the opposite is true for the corona. The Mg II $h+k$ and C IV emissions from both CM Dra and Rst 137 B are very close to these observed saturation levels. The saturation for M stars seems to occur somewhere at rotation periods above 5 days (for G stars the limit is 3 days). We suggest that the photospheres of stars at this saturation level (like CM Dra and Rst 137 B) are almost completely covered with equipartition magnetic fields. We further suggest (based on model computations) that another physical constraint behind the saturation is in the limited amount of subphotospheric mechanical flux, the driver for coronal heating. In addition, the observations indicate that also for M stars there is a dependence of the activity on rotation (for periods longer than the saturation value). Therefore we consider our results, similarly to Giampapa and Liebert (1986), to favour a rotation-dependent distributed dynamo generating magnetic flux in totally convective stars.

Key words: stars: activity – stars: chromospheres of – stars: binaries: close – stars: pre-main sequence – stars: M dwarfs

1. Introduction

One of the important questions in stellar astrophysics is the extent of magnetic activity in the least massive M dwarfs. The activity levels of these stars provide strong constraints for our understanding both of stellar structure and of magnetic field amplification. Stellar structure models for M dwarfs suggest that main-sequence stars later than about dM 3 are fully convective (Copeland et al., 1970; Grossman et al., 1974). Some researchers favour a class of dynamo models known as the "shell-models". The efficiency of shell models depends on convective "overshoot" from the base of the convective zone into the radiative core of the star (see e.g., Schmitt et al., 1984). This allows a large storage of magnetic flux in the radiative layer just below the convective zone. If magnetic amplification in fact occurs at the base of the convective zone (Galloway and Weiss, 1981; Rosner and Vaiana, 1980; Belvedere, 1983), then the lack of this zone in very low mass stars (fully convective) should result in a significant decrease in magnetic activity (Giampapa and Liebert, 1986).

Current observational results for stars that are presumed to be fully convective are very inconclusive. The classical spectroscopic study by Joy and Abt (1974), followed by the more complete work by Stauffer and Hartmann (1986), suggest an increasing percentage of stars with Balmer emission lines (dMe stars) later than M 5. Giampapa and Liebert (1986) found in their important work that both Hα emission and non-emission stars can be found at spectral types later than M 5.5. They give evidence that the non-emission line stars are very slow rotators, and consider their results to favour a rotation-dependent distributed dynamo as a viable model for the generation of magnetic flux in the very low mass stars (contrary to the shell-model).

In extensive X-ray surveys using EINSTEIN data, Golub (1983) and Bookbinder (1985) found a qualitative change in the behaviour of the quiescent X-ray luminosity, L_x, at dM 5. While earlier stars show a range of almost three orders of magnitude in L_x (10^{27}–10^{30} erg s^{-1}), stars later than dM 5 appear to have only solar-like values of L_x (about 10^{27} erg s^{-1}). On the other hand, Rucinski (1984) found that this drop is not so significant in the ratio of the X-ray flux to the bolometric flux.

The question about activity vs. spectral type is not well formulated without including stellar rotation rate and age in the analysis. Any drop in activity might simply mean, for example, a drop in the stellar rotation rate. In particular, hydromagnetic dynamo models indicate a linear dependence of the mean magnetic energy and the kinetic energy of the mean flow on the rotation rate (see Fig. 1 in Brandenburg et al., 1989). Recent work on cool stars has demonstrated a fall-off of the upper atmosphere

---

Send offprint requests to: O. Vilhu

* Based on observations with the International Ultraviolet Explorer (IUE) obtained at the Villafranca satellite tracking station of the European Space Agency and at NASA/Goddard Space Flight Center

activity with Rossby number (rotation period/convective turnover time) and age (Noyes et al., 1984; Vilhu, 1984; Simon et al., 1985). The dependence on age could be due to decrease of rotation rate, as a result of rotational spindown (see e.g., Vilhu and Moss, 1986).

We present IUE observations of two active M dwarfs that we presume to be almost totally convective and for which the rotation rate or age are known. The first of these stars, CM Draconis (Gl 630.1), is an old Population II binary with its components in tidally induced rapid rotation ($P = 1.27$ d, dM 4 + dM 4). The other one, Rossiter 137 B, forms with HD 36705 (AB Dor) a visual pair of young active stars. We also compare these results with those for other M dwarfs, particularly AU Mic and YZ CMi, that have known rotational periods and measured ultraviolet emission line fluxes.

2. Observations

2.1. *CM Draconis*

There are very few M dwarfs with known rotational periods. AU Mic ($P = 4.86$ d, M 1.6) and YZ CMi ($P = 2.78$ d, M 4.3) are previously studied examples of active, rapidly rotating M dwarfs (Linsky et al., 1982). They are classical Population I flare stars. AU Mic has a radiative core, whereas YZ CMi is a borderline case and may be fully convective.

CM Dra (dM 4 + dM 4) is the least massive eclipsing binary known, with components of masses $0.24\,M_\odot$ and $0.21\,M_\odot$ and radii of $0.25\,R_\odot$ and $0.24\,R_\odot$ (Lacy, 1977). Though confirmed by Lacy, the spectral types seem to be early for stars of this mass. Nevertheless, the masses are more reliably determined than the spectral types. On the basis of these masses, the components of CM Dra system should be fully convective (Paczyński and Sienkewich, 1984). A conflicting model by Cox et al. (1981) predicts that the cores of very late M dwarfs are radiative.

Besides being fully convective, two pieces of evidence suggest that CM Dra is much older than the classical flare stars: (1) A third star, a common proper motion white dwarf, is present in the system. (2) The space velocity of 163 km s^{-1} is characteristic of population II objects. On the other hand, the period of CM Dra is unusually short (1.27 d). Because of its age, we assume that the orbital and spin rotations have been synchronized. CM Dra is in many ways a miniature, and much older, version of the classical flare star YY Gem (dM 1 e + dM 1 e, $P = 0.82$ d). The eclipses in CM Dra (Lacy, 1977) are very pronounced (0.75 mag) and very brief.

The very low flaring rate of CM Dra, 0.02 to 0.05 flares per hour, is almost two orders of magnitude lower than that of classical population I flare stars of similar spectral type (Lacy, 1977; Lacy et al., 1976). It is possible that the low flaring activity is due to the star's advanced age, but the rotation period of CM Dra suggests a high overall level of activity. The Balmer lines of CM Dra are seen strongly in emission, which also suggests enhanced flare activity.

We observed CM Dra on 5–6 July 1986, using two continguous IUE shifts (US 1 + ESA) to obtain a deep SWP and a short LWP exposure (both in low resolution). One useful LWR spectrum existed in the IUE archive, so this was compared with the new one. Table 1 gives a log of the observations. The primary eclipse starts at phase 0.98 and ends at phase 0.02. Hence LWP 8554 was obtained during the primary eclipse (totality lasts just a few minutes), while LWR 14341 and SWP 28619 are out-of-eclipse spectra. Due to the very brief eclipse, only about 15% of the light was lost during the exposure of LWP 8554.

Table 1. IUE observations of CM Dra

Image (low res.)	Start (JD) +2440000	Exposure time (min)	Phase interval
LWR 14341	5248.127	120	0.05–0.11
LWP 8554	6617.890	90	0.97–0.02
SWP 28619	6617.335	790	0.53–0.96

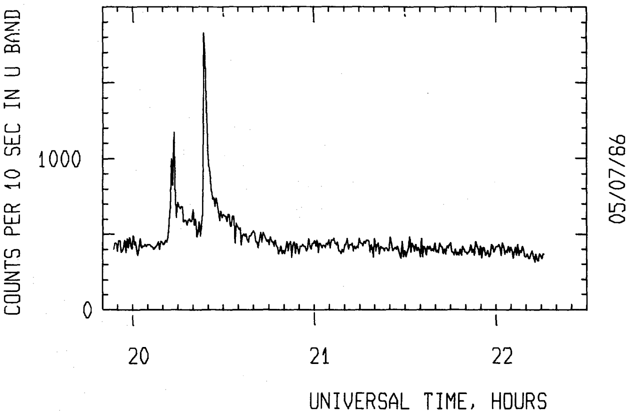

Fig. 1. The two flares of CM Dra observed during the exposure of SWP 28619

To monitor flares, we observed CM Dra photometrically with the Kitt Peak ♯2 0.9 m telescope (JD 2446617.71–.96, *UBV*-bands) and with the Crimean observations two flares (0.6 and 1.1 mag in the *U*-filter) were observed near the beginning of the SWP 28619 exposure (see Fig. 1). The two flares during the photometric monitoring period of 8 h indicate a higher flaring rate than that observed by Lacy (1977) (during 18 h Lacy observed one flare). The difference is not, however, statistically significant. The Kitt Peak photometry confirmed that the ephemeris of light minimum JD 2442893.93249 and the orbital period 1.26838965 d (Lacy, 1977) very accurately predicted the time of primary minimum.

The Mg II h + k (2800 Å) emission (Fig. 2) was easily detectable. However, only upper limits could be derived for most emission lines from the SWP spectrum (Fig. 3). These upper limits were measured using the algorithm by Bennett (1987), which is optimized for IUE low-dispersion spectra of late-type stars and permits a systematic estimate of errors in the measured quantities (Table 2). The only emission line in the SWP spectrum with a measurable flux was Si II 1817. This possible detection was due to the lower noise in the long wavelength part of the SWP spectrum. However, it is safest to assume that all the fluxes of Table 2 are upper limits, only.

The bolometric fluxes in Table 2 were computed using BC = 2.38 (Lacy, 1977). The surface fluxes were then computed from $F = f/f(\text{bol})\,\sigma T_{\text{eff}}^4$, using $T_{\text{eff}} = 3350$ K, which was derived from $B - V = 1.60$ with Böhm-Vitense's (1981) calibration. The linear fit T_{eff} vs. $B - V$ by Pettersen (1983) leads to the nearly same value (3320 K). The bolometric flux during LWP 8554 was smaller due to the eclipse.

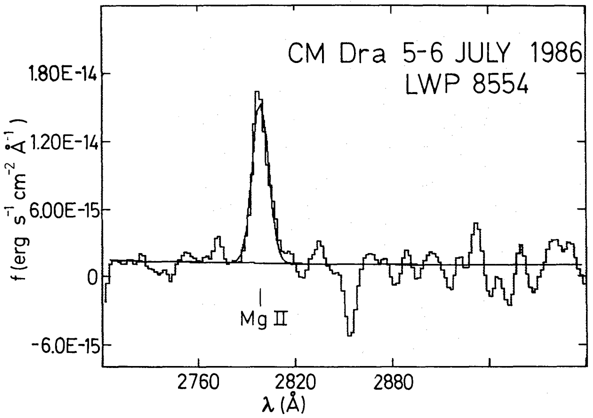

Fig. 2. The Mg II h + k 2800 emission in the low-resolution spectrum LWP 8554 of CM Dra

The upper limits can be compared with the Si II 1817 and Mg II 2800 detections. Oranje (1986) derived tight relations, using a large sample of cool stars, between Mg II, Si II, and TR fluxes, where TR (transition region) stands for the combined N V 1240 + Si IV 1400 + C IV 1550 emission. For CM Dra we derived the upper limit $F(\mathrm{TR}) < (3.9 \pm 1.2)\ 10^5\ \mathrm{erg\,s^{-1}\,cm^{-2}}$. At the observed Mg II and Si II flux values of Table 2, this upper limit matches well with other dMe stars in the sample of Oranje (see his Figs. 4 and 5; dMe stars deviate slightly from the normal scaling laws in the sense that the transition region fluxes are higher at a fixed chromospheric flux). This comparison gives an indication that the C IV upper limit of Table 2 is close to the actual value.

2.2. *Rossiter 137 B*

Rst 137 B is a proper motion and radial velocity companion of the active young pre-main-sequence star AB Dor (HD 36705, K 1 IV, $m_V = 7$), at a separation of 10″. The age of the system is between 1 and 30 million years (Vilhu et al., 1987). This young pair of stars, in the direction of the Magellanic Clouds in the southern hemisphere, is a good target to study mass-dependent effects of early stellar evolution.

Innis (1986) estimated $m_V = 13.0$ and Sp = M 3–M 4, and Vilhu and Linsky (1987) measured its X-ray luminosity to be close to the saturation level defined by very young stars and rapid rotators. Not much more is known about the star. The brighter companion, AB Dor, has been studied more extensively (e.g. Rucinsky, 1985; Innis et al., 1985; Collier-Cameron et al., 1988; Vilhu et al., 1987).

Rst 137 B was observed with the IUE's LWP camera (in low resolution) on 9 March 1987, when the position angle (the angle between north and the major axis of the large aperture) was about 160°. This allowed us to move the bright companion AB Dor (10″ south of Rst 137 B) outside the large aperture after pointing on it, by making an offset of 5″. However, due to the brightness of AB Dor, some scattered light from it was left in the aperture. This, however, did not prevent us from measuring the Mg II 2800 emission of Rst 137 B, since the observing date was selected such that the wavelength dispersion was running from the east to the west (see Fig. 4).

The measured Mg II h + k emission line flux of Rst 137 B is $(1.0 \pm 0.2)\ 10^{-13}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ corresponding to the surface flux (on the star) $(8 \pm 3)\ 10^5\ \mathrm{erg\,cm^{-2}\,s^{-1}}$. The latter value is based on fixed visual magnitude $V = 13.0$, but allowing the spectral type to vary by 2 sub-classes between M 2.5 and M 4.5. In this way, the bolometric correction varied from −1.6 to −2.5

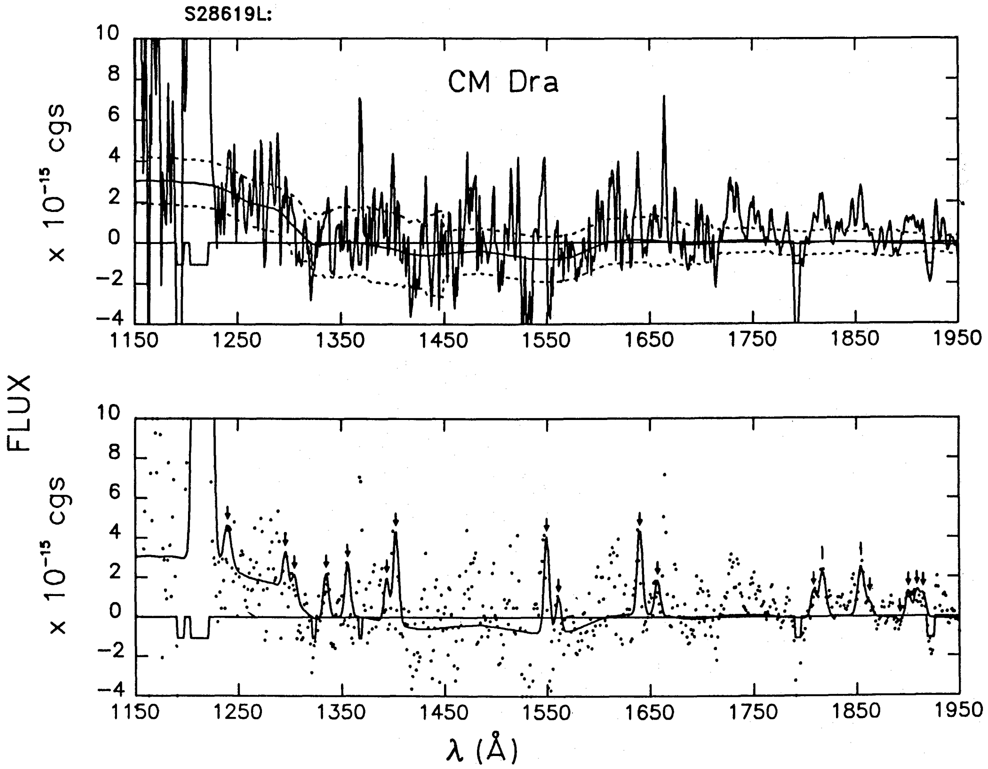

Fig. 3. The low-resolution spectrum SWP 28619 of CM Dra, showing upper limits (arrows) for emission lines with probable detections at Si II 1817 and Al III 1854. In the upper panel, the solid line is the fit to the residual background, and the dashed lines represent the one sigma error in the fit. The lower panel shows the fit (solid line) and the observed spectrum (dots)

Table 2. IUE fluxes of CM Dra ($\text{erg cm}^{-2}\,\text{s}^{-1}$). f is the observed flux (at the Earth). F is the surface flux at the star

Image	f(Mg II) (10^{-14})	f(C IV) (10^{-14})	f(Si II) (10^{-14})	f(bol) (10^{-9})	F(Mg II) (10^{5})	F(C IV) (10^{5})	F(Si II) (10^{5})
LWR 14341	19.2 ± 2.0			1.67	8.2 ± 1.0		
LWP 8554	18.2 ± 2.0			1.42	9.1 ± 1.0		
SWP 28619		<3.8	~ 2.0	1.67		<1.6	0.8 ± 0.2

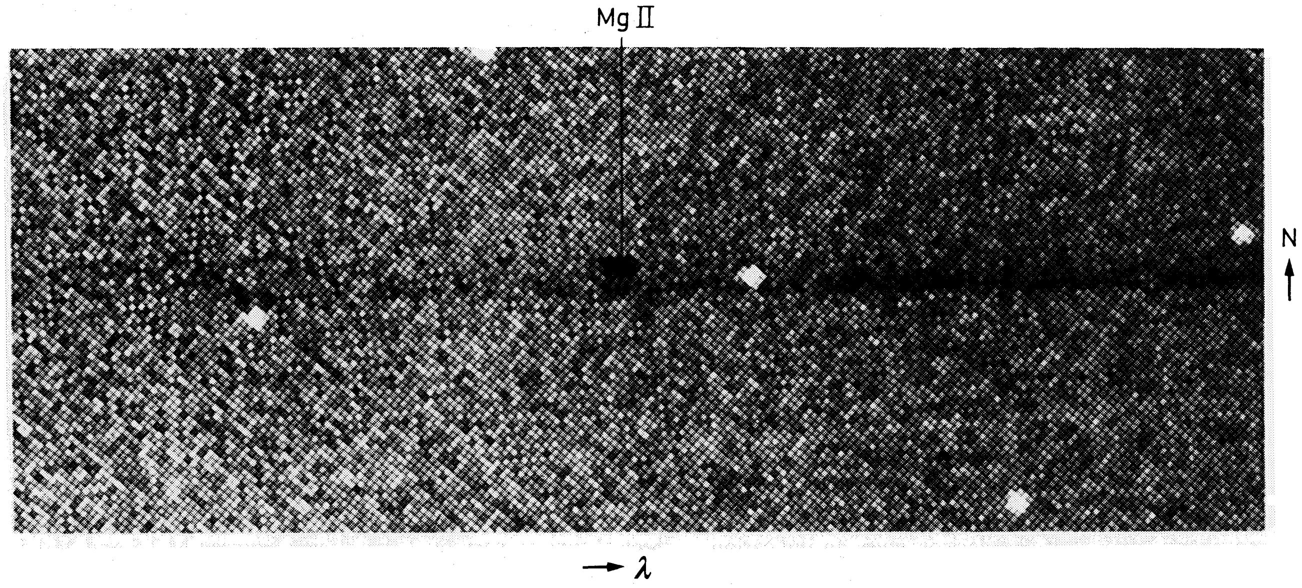

Fig. 4. The raw IUE image LWP 10306 of Rst 137 B, observed 9 March 1987. The wavelength runs from left to right. The dark spot is the Mg II 2800 Å emission from Rst 137 B, and scattered light from the continuum of AB Dor is seen (10″ south of Rst 137 B)

(Johnson, 1966). Using Pettersen's (1983) calibrations, the $(B-V)$ colour range was 1.54–1.64. The calibrations $B-V$ vs. T_{eff} by Pettersen (1983) and by Böhm-Vitense (1981) are quite similar, leading to $T_{\text{eff}} = 3200$–3400 K. The surface fluxes were then computed from $F = f/f(\text{bol})\,\sigma T_{\text{eff}}^4$ where $f(\text{bol}) = 2.7\;10^{-5}\;10^{-0.4(V+\text{BC})}\,\text{erg cm}^{-2}\,\text{s}^{-1}$. For comparison, the X-ray surface flux of Rst 137 B from Vilhu and Linsky (1987) is $(7 \pm 2)\;10^{6}\,\text{erg cm}^{-2}\,\text{s}^{-1}$.

Vilhu and Linsky (1987) found that the fractional X-ray luminosities $f(X)/f(\text{bol})$ for both components of the AB Dor + Rst 137 B system are very similar and close to the value of 10^{-3}. For stars later than G0, this is the spectral-type independent saturation level. A star with a younger age or higher rotation rate cannot rise above this level. The physical reason behind the saturation is probably in the limited amount of mechanical convective energy available (Vilhu and Walter, 1987; Vilhu, 1987).

3. Discussion and comparison with other data

In this section we compare our observations of CM Dra and Rst 137 B with other relevant data.

Figures 5 and 6 show the surface fluxes of Mg II h + k and C IV 1550 emission lines as a function of $[B-V]$ for a large sample of cool stars. These plots are extensions (towards cooler stars) of those given by Vilhu and Walter (1987). In addition to the references given by Vilhu and Walter and to the results of this paper, Figs. 5 and 6 were compiled using the following references:

Mg II:	late K – M	stars:	Linsky et al. (1982), Oranje (1986), Doyle (1987)
	RS CVn	stars:	Basri (1987)
	FK Com	stars:	Bopp and Stencel (1981)
	Naked TTau	stars:	Walter (1986)
	TTau	stars:	Simon et al. (1985)
C IV:	M	stars:	Linsky et al. (1982)
	FK Com	stars:	Bopp and Stencel (1981)
	RS CVn	stars:	Basri et al. (1985)
	TTau	stars:	Simon et al. (1985)

We presume that the fluxes of M stars represent quiescent levels, but in many cases this cannot be tested, due to the lack of simultaneous photometric monitoring. We detected 2 flares from CM Dra during the SWP exposure. Their influence might have remained small, since the upper limits of the fluxes still are below the saturation levels. Linsky (1988) gives a summary of multi-wavelength observations of flares in M dwarfs, and finds that

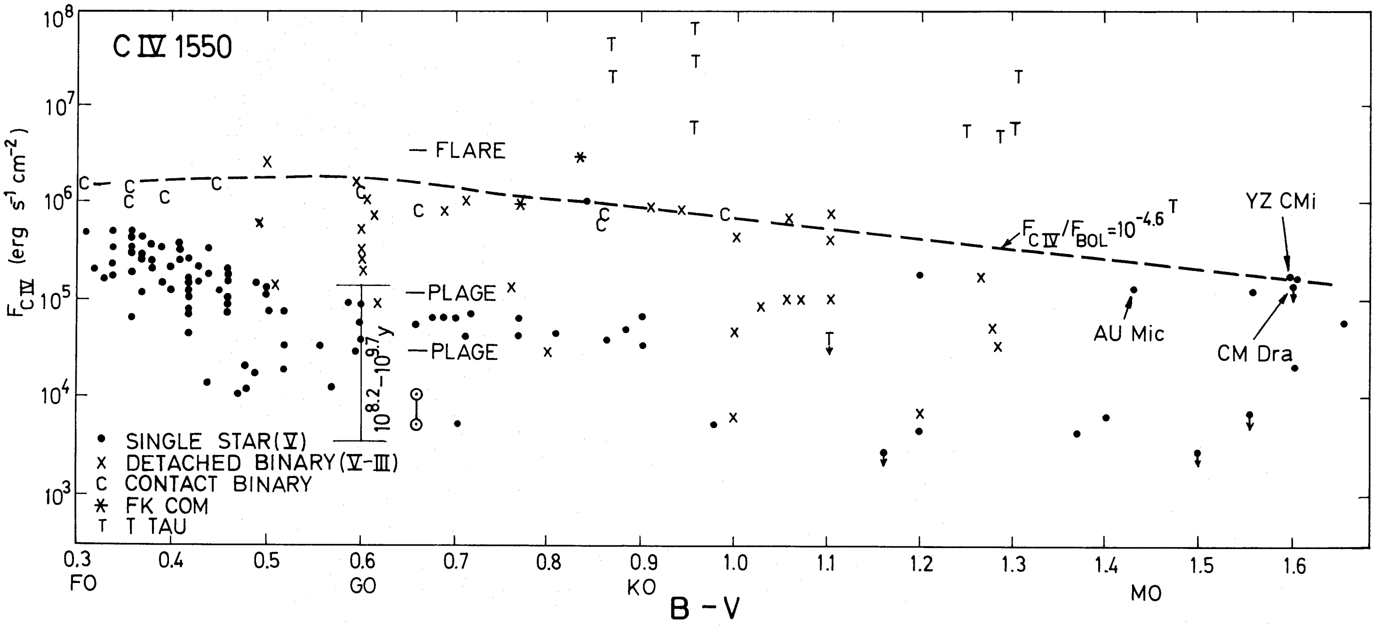

Fig. 5. The surface flux of the transition region C IV 1550 Å emission line vs. colour. The dotted line gives the upper boundary (excluding T Tau stars)

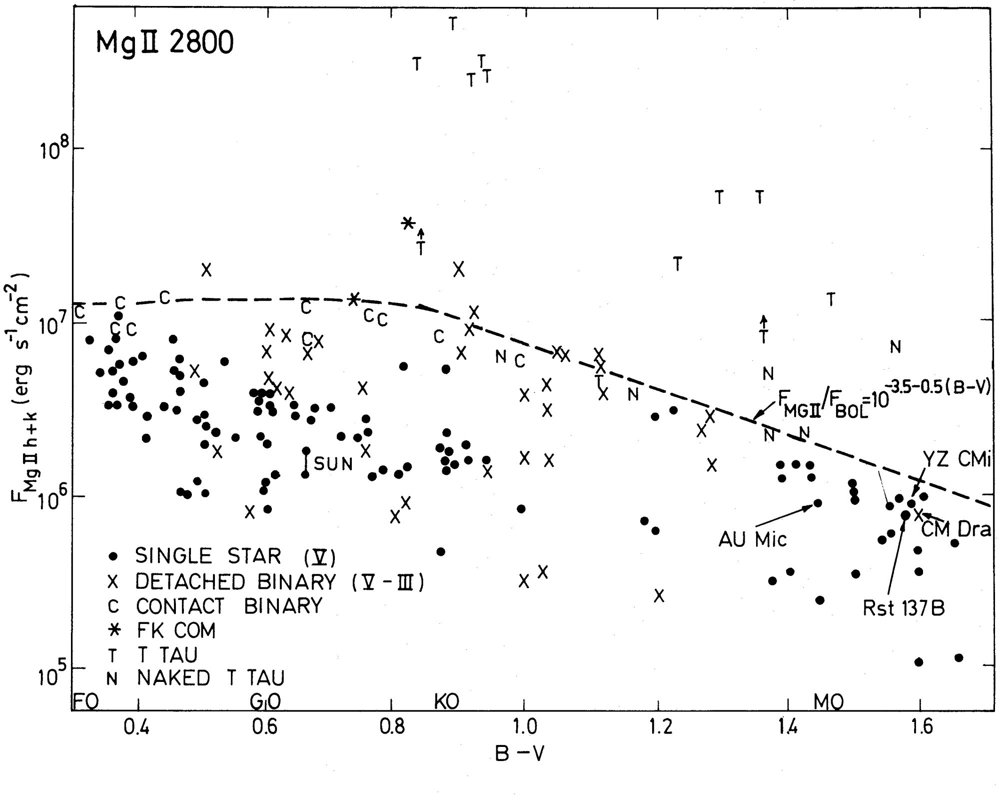

Fig. 6. The surface flux of the chromospheric Mg II h+k 2800 Å emission line vs. colour. The dotted line gives the upper boundary (excluding TTau stars)

during the strongest observed flares the transition region fluxes (like C IV) are enhanced by factors of 3–4. Hence, during the long (790 min) exposure of SWP 28619 even several flares do not affect the mean fluxes appreciably, since the ratio quiet time/flaring time is so high (two observed flares of CM Dra in 8 h with duration of 5 min gives for the ratio a value of 48).

TTauri stars are shown just for comparison. Certainly in their activity some other physical mechanism (accretion?) contributes, in addition to the dynamo-driven activity. In post-TTau stars ("Naked TTau"; see Walter, 1986) the dusty envelopes have disappeared (or never formed), and in these stars we see the surface magnetic activity driven by the dynamo. The four stars discussed in the text are marked in Figs. 5 and 6. We summarize their parameters in Table 3.

As seen in Fig. 5, the M type rapid rotators AU Mic, YZ CMi, and the upper limit of CM Dra are very close to the saturation

Table 3. The M dwarfs discussed in the text

Star	Sp	$B-V$	$m(V)$	BC	P(d)	F(line)/ F(bol) Mg II (10^{-4})	C IV (10^{-5})	F(line) Mg II (10^{6})	C IV (10^{5})	Ref.
AU Mic	M 1.6 e	1.40	8.75	−1.40	4.86	0.7	1.2	0.9	1.3	1, 2
YZ CMi	M 4.3 e	1.59	11.24	−2.4	2.78	1.2	2.5	0.9	1.8	1, 2
CM Dra	M 4+M 4	1.60	12.90	−2.38	1.27	1.2	<1.8	0.8	<1.3	3
Rst 137 B	M 3.5	1.60	13.0	−2.10	?	1.0	–	0.8	–	3

References: 1) Linsky et al. (1982); 2) Oranje (1986); 3) this study, mean values

boundary: $\log(F(\mathrm{C\,IV})/F(\mathrm{bol}))=-4.6$. Despite a factor of 4 difference in rotation period, the F_l and F_l/F_{bol} of Table 3 are essentially identical due to the well known saturation. The saturation of the transition region fluxes of F – K stars taken place at a Rossby number (Ro = rotation period/convective turnover time at the bottom of the convective zone) about 0.3 (Vilhu, 1984). From mixing length models, turnover times around 60 days follow for almost completely convective M stars. Hence, the Rossby numbers of AU Mic, YZ CMi, and CM Dra are between 0.08 and 0.02. Plotting $F(\mathrm{TR})/F(\mathrm{bol})$ versus Ro, one finds these stars on the flat part occupied by G – K type very rapid rotators and short period binaries (see Fig. 2e of Vilhu, 1984). We expect even relatively slowly rotating M dwarfs (P(rot) < 20 d) to be saturated, *if* they follow this same tendency, contrary to G stars for which periods less than 3 days are needed to reach the saturation level. In this sence the M dwarfs of Table 3 do not show any peculiar behaviour when comparing with G – K stars. We also suggest that the rotation period of Rst 137 B is short, although not known.

The upper boundary in Fig. 6, as measured by $F(\mathrm{Mg\,II})/F(\mathrm{bol})$, has a small spectral-type dependent decrease $\log(F(\mathrm{Mg\,II})/F(\mathrm{bol}))=-3.5-0.5\,(B-V-0.9)$, for $B-V>0.9$. But again, the M dwarfs of Table 3 are close to the upper boundary. This underactivity in Mg II emission of M dwarfs, as compared with the C IV emission and with G – K stars, can also be seen in flux-flux diagrams by Oranje (1986). In these plots, at a fixed TR level, the dMe stars have weakest Mg II fluxes. It is now clear that at both ends of the dynamo region (F and M stars) one observes the decline of some indicator for the saturation level: F stars show a rapid decline of X-ray emission towards earlier spectral types, while the chromospheric and transition region fluxes remain nearly constant, whereas M stars show more decrease in the chromospheric emission towards later spectral types. Therefore the coronae of F stars weaken first when the convective layer becomes shallower, and the chromospheres of M stars weaken first when the convective layer becomes deeper.

4. Conclusions and physical interpretation of the saturation

1. We collect here the relations defining the chromospheric-TR-coronal *saturation* levels of main-sequence stars, as estimated from Figs. 5 and 6 and from the X-ray plot given in Vilhu and Walter (1987), Vilhu and Linsky (1987), and Vilhu (1987) (the flux units are erg s^{-1} cm^{-2}):

$$\begin{array}{lll}
\log(F(\mathrm{Mg\,II})) & =7.0 & 0.3<B-V<1.0 \\
\log(F(\mathrm{Mg\,II})/F(\mathrm{bol})) & =-3.5-0.5\;(B-V-0.9) & 1.0<B-V<1.6 \\
\log(F(\mathrm{C\,IV})) & =6.0 & 0.3<B-V<1.0 \\
\log(F(\mathrm{C\,IV})/F(\mathrm{bol})) & =-4.6 & 1.0<B-V<1.6 \\
\log(F(\mathrm{X})) & =4.5+5\;(B-V) & 0.1<B-V<0.6 \\
\log(F(\mathrm{X})/F(\mathrm{bol})) & =-3.0 & 0.6<B-V<1.6
\end{array} \qquad (1)$$

As noted by Bookbinder (1985), many G stars might be binaries with active dMe companions which could contribute to the X-ray flux. However, this does not change the G star saturation value (F_x/F_{bol}) if the companion dMe stars also obey the saturation (the same $F_x/F_{\mathrm{bol}}=-3$). This value was estimated from the optically selected (nearly volume-limited) M dwarf data otained by Bookbinder (1985). However, in an X-ray selected sample of 124 late-type (F – M) stars, Fleming et al. (1989) found several stars above this level up to $F_x/F_{\mathrm{bol}}=10^{-2.3}$. Their data suggests that the saturated F_x-levels are constant for $B-V>0.6$ ($7\;10^{7}$ erg cm^{-2} s^{-1}).

2. Plotting the differential emission measure versus temperature, G stars have (at saturated levels) the largest emission measures at all temperatures. This means that the radiative losses of the upper atmosphere can be largest for G stars. F stars have stronger chromospheres and transition regions than M stars, but the opposite is true for the corona. Equipartition photospheric magnetic fields of F stars are less than 1000 gauss, compared with 4000 to 5000 gauss in active M stars (Saar et al., 1987; see also Saar and Linsky 1985). In F stars, the confining and heating power might then be considerably reduced, which could be an explanation for weak coronae in F stars, while their chromospheres and transition regions still are significant.

The most direct evidence for magnetic fields in M stars comes from the work by Saar et al. (1987). Using phtospheric absorption lines at 2.2 microns, they found that some flare stars have equipartition fields filling more than 80% of their surface. AU Mic has 4000 gauss fields filling 90% of its surface and EV Lac, having the latest spectral type M 4.5 e in the sample, was observed to have 5200 gauss fields with a filling factor of 90%.

These direct measurements of photospheric magnetic fields are compatible with our results of saturation in the chromospheric-TR-coronal radiative losses in F – M stars. The most active (saturated) stars are rapid rotators (rotational periods less than 1/3 of the convective turnover time at the bottom of the convective envelope). As discussed in the previous chapter, the transition region fluxes of G stars saturate if the rotation period is less than 3 days. The saturated stars are either very young stars (with little braking in their rotation; we suggest that the activity of Rst 137 B is due to its sufficient fast (< 20 d) rotation, which in turn is due to the small age) or components of close binaries with tidally forced rotation (like CM Dra). Their surfaces appear to be almost totally filled with photospheric equipartition magnetic field ($p_g = B^2/8\pi$). This is the first reason for the saturation: the surface is already "full". All these results together give evidence for a rotation-dependent distributed dynamo generating magnetic flux in the very low mass stars. This conclusion was reached already by Giampapa and Liebert (1986) and Giampapa (1987).

3. While our results suggest that some sort distributed dynamo operates in totally convective M stars, this does not mean that the interface between the convective envelope and radiative core could not be important, giving some extra efficiency to the dynamo in G stars (shell dynamo). Here the key issue seems to be the possible differences in the activity vs. rotation relationships between G and M stars (looking at e.g., the Rossby-number scaling laws as discussed above). However, the lack of sufficient rotational velocity data for M stars makes this comparison difficult.

Bopp et al. (1981) found that at $v \sin i \leqq 3\,\mathrm{km\,s^{-1}}$ the M stars are non-dMe stars and the activity appears sharply at $5\,\mathrm{km\,s^{-1}}$. The increase of the rotational velocity above $5\,\mathrm{km\,s^{-1}}$ does not seem to enhance the activity. In agreement with this result, Vogt et al. (1983) found that all M dwarfs rotating faster than $5\,\mathrm{km\,s^{-1}}$ are emission line dMe stars. (For a dM 3 star, with a radius of $0.4\,R_\odot$, the rotational periods corresponding to equatorial velocities $3\,\mathrm{km\,s^{-1}}$ and $5\,\mathrm{km\,s^{-1}}$ are $7\overset{\mathrm{d}}{.}6$ and $4\overset{\mathrm{d}}{.}6$, respectively.) Further, Agrawal et al. (1986) observed $L_\mathrm{x}/L_\mathrm{bol}$-values close to the X-ray saturation value (10^{-3}) for 7 M dwarfs with known rotational periods (< 5 d). Hence, it seems that the saturation of activity in M dwarfs occurs at rotational periods somewhere between 5 and 10 days. This would mean that the scaling laws "activity vs. Rossby number", derived from G – K stars, are not valid for M dwarfs, or else the convective turnover times of M dwarfs are shorter than 20 days, less than the mixing length models predict.

A photometric study by one of us (C.A.) indicates that this indeed might be the case: Gl 83.1 (dM 8 e) has a preliminary photometric period around 20 days, for another star Gl 866 (dM 5.5 e) it is 6–7 days. Agrawal et al. (1986) give the $f_\mathrm{x}/f_\mathrm{bol}$-values $10^{-3.57}$ and $10^{-4.0}$, respectively, for these totally convective stars. If we consider the saturation value $f_\mathrm{x}/f_\mathrm{bol} = 10^{-3}$ [(Eq. 1)] for F – G – K-early M stars, then clearly the convective turnover times for the totally convective stars Gl 83.1 and Gl 866 are less than 20 days, or else the common scaling laws "flux vs. Rossby number" are not valid for M dwarfs.

4. As suggested by Mullan (1984), Vilhu and Walter (1987), and Vilhu (1987), another main constraint (in addition to the 100% surface coverage) could be in the maximum mechanical flux available in subphotospheric layers. We reproduce as Fig. 7 the plot from Vilhu (1987), where the maximal mechanical fluxes (MECHANICAL) just below the photosphere (at $\tau \approx 1$)

$$F^{(\mathrm{mech})} = 1/2\,\varrho \boldsymbol{u}\,(u_\parallel^2 + u_\perp^2) \tag{2}$$

were computed and a comparison was made with the saturated radiative losses ($u^\perp$ is the horizontal and $u^\parallel$ the vertical component of the velocity vector $\mathbf{u}$). Mixing length models were used, in which $u_\perp = 0$. The total radiative loss (SATURATION) was estimated from static loop models that satisfy the constraints given by the upper limits of the measured X-ray and C IV fluxes. The chromospheric contribution was neglected, since the resulting loop emission of saturated stars was much larger than the Mg II emission (compare Figs. 6 and 7).

In addition, the vertical component of the maximal mechanical flux

$$F_\parallel^{(\mathrm{mech})} = 1/2\,\varrho u_\parallel\,(u_\perp^2 + u_\parallel^2) \tag{3}$$

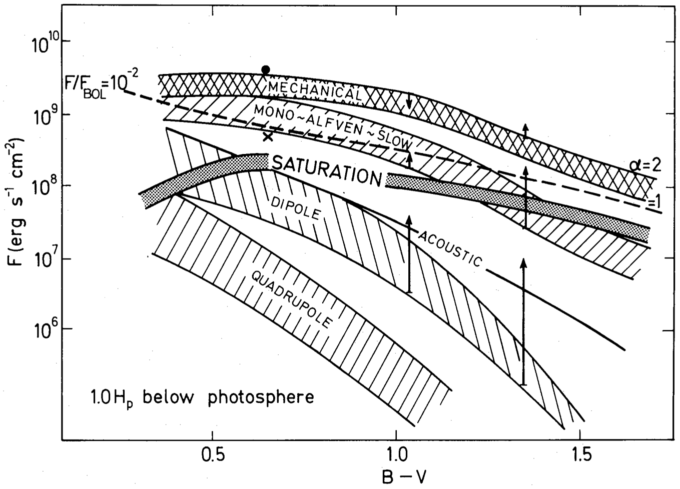

Fig. 7. Observed total saturated radiative losses (SATURATION) and computed maximal subphotospheric mechanical fluxes (MECHANICAL) of mixing length models (with the mixing length $\alpha = 1 - 2$). The dot and the cross denote the maximum values contained in the vertical (dot) and horizontal (cross) flows in a solar granular model of Steffen (1987). The arrows show the effect of changing the gravity from $\log g = 4.5$ to 2.0. Estimates for acoustic fluxes and Alfven waves in equipartition magnetic field are also shown (from Vilhu, 1987)

was computed from a solar granular model by Steffen (1987). The value obtained for $F_\parallel$ is indicated by a dot in Fig. 7. The fluxes from mixing length models and Steffen's model are nearly of the same size. However, it might be that Eq. (3) gives a too optimistic estimate of the mechanical energy involved, in particular when the horizontal motions contribute mainly to the excitation of waves (e.g., by twisting and shaking the flux-tubes). We computed the maximal flux (vertical component) of the energy contained in horizontal motions $1/2\,\varrho u_\parallel\,u_\perp^2$. This value, indicated in Fig. 7 by a cross, is only slightly above the observed saturation level. A high efficiency seems therefore necessary to explain the emission limit of fully saturated stars in terms of the horizontal mechanical flux.

Although the computations in Fig. 7 are very crude and preliminary (for some more details see Vilhu, 1987), the subphotospheric mechanical fluxes are not very much higher than the observed total radiative losses of saturated stars. In addition to the geometrical factor (the whole surface covered), this is apparently the second physical reason for the saturation, especially for later type stars. However, this conclusion is based on non-magnetic convection. On the other hand the observations seem to indicate that the cool star photosphere can tolerate almost total filling with equipartition magnetic field without suppressing too much the convection. In saturated stars (like CM Dra and Rst 137B) we might see such a situation.

Acknowledgements. The data analysis was performed at the Colorado Regional Data Analysis Facility (RDAF), which is supported by NASA grant NAG 5-26409 to the Univeristy of Colorado. We are grateful to Dr. J. Bennett, for his algorithm to detect upper limits for emission lines, and to Dr. R. Gershberg for organizing the Crimean photometry. Especially we thank Mark Giampapa, the referee, for many valuable comments.

References

Agrawal, P.C., Rao, A.R., Sreekantan, B.V.: 1986, *Monthly Notices Roy. Astron. Soc.* **219**, 225
Basri, G.: 1987, *Astrophys. J.* **316**, 377

Basri, G., Laurent, R., Walter, F.: 1985, *Astrophys. J.* **298**, 761

Belvedere, G.: 1983, in *Activity in Red Dwarf Stars*, eds. P.B. Byrne, M. Rodonò, Reidel, Dordrecht, p. 579

Bennett, J.: 1987, Ph.D. Thesis, Univ. of Colorado, Boulder

Böhm-Vitense, E.: 1981, *Ann. Rev. Astr. Astrophys.* **19**, 295

Bookbinder, J.: 1985, Ph. D. Thesis, Harvard University

Bopp, B.W., Noah, P.V., Klimke, A., Africano, I.: 1981, *Astrophys. J.* **249**, 210

Bopp, B., Stencel, R.: 1981, *Astrophys. J. Letters* **247**, L 131

Brandenburg, A., Moss, D., Tuominen, I.: 1989, *Geophys. Astrophys. Fluid Mech.* (in press)

Collier-Cameron, A., Bedford, D., Lloyd-Evans, T., Rucinski, S., Vilhu, O., White, N.: 1988, *Monthly Notices Roy. Astron. Soc.* **231**, 131

Copeland, H., Jensen, J.O., Jorgensen, H.E.: 1970, *Astron. Astrophys.* **5**, 12

Cox, A.N., Shaviv, G., Hodson, S.W.: 1981, *Astrophys. J.* **245**, L 37

Doyle, J.G.: 1987, *Monthly Notices Roy. Astron. Soc.* **224**, 1 P

Fleming, T.A., Gioia, I.M., Maccacaro, T.: 1989, *Astrophys. J.* (in press)

Galloway, D.J., Weiss, N.O.: 1981, *Astrophys. J.* **243**, 945

Giampapa, M.S., Liebert, J.: 1986, *Astrophys. J.* **305**, 784

Giampapa, M.S.: 1987, in *Cool Stars, Stellar Systems, and the Sun*, eds. J. Linsky, R. Stencel, Springer, Berlin, Heidelberg, New York, p. 236

Golub, L.: 1983, in *Activity in Red Dwarf Stars*, eds. P.B. Byrne, M. Rodonò, Reidel, Dordrecht, p. 83

Grossman, A.S., Hayes, D., Graboske, H.C., Jr.: 1974, *Astron. Astrophys.* **30**, 95

Innis, J.L.: 1986, private communication

Innis, J.L., Robinson, R.D., Coates, D.W., Thompson, K.: 1985, *Proc. Astr. Soc. Australia* **6**, 156

Johnson, H.L.: 1966, *Ann. Rev. Astron. Astrophys.* **4**, 193

Joy, A., Abt, H.: 1974, *Astrophys. J. Suppl.* **28**, 1

Lacy, C.H., Moffett, T.J., Evans, D.S.: 1976, *Astrophys. J. Suppl.* **30**, 85

Lacy, C.H.: 1977, *Astrophys. J.* **218**, 444

Linsky, J.L.: 1988, in *Multiwavelength Astrophysics*, ed. F. Cordova, Cambridge University Press, Cambridge (to appear)

Linsky, J.L., Bornman, P.L., Carpenter, K.G., Wing, R.F., Giampapa, M.S., Worden, S.P., Hege, E.K.: 1982, *Astrophys. J.* **260**, 670

Mullan, D.J.: 1984, *Astrophys. J.* **282**, 603

Noyes, R.W., Hartmann, L.W., Baliunas, S.L., Duncan, D.K., Vaughan, A.H.: 1984, *Astrophys. J.* **279**, 763

Oranje, B.J.: 1986, *Astron. Astrophys.* **154**, 185

Paczyński, B., Sieniewich, R.: 1984, *Astrophys. J.* **286**, 332

Pettersen, B.R.: 1983, in *Activity in Red Dwarf Stars*, eds. P.B. Byrne, M. Rodonò, Reidel, Dordrecht, p. 17

Rosner, R., Vaiana, G.S.: 1980, in *X-ray Astronomy*, eds. R. Giacconi, G. Setti, Reidel, Dordrecht, p. 129

Rucinski, S.M.: 1984, *Astron. Astrophys.* **132**, L 9

Rucinski, S.M.: 1985, *Monthly Notices Roy. Astron. Soc.* **215**, 591

Saar, S.H., Linsky, J.L.: 1985, *Astrophys. J. Lett.* **299**, L 47

Saar, S., Linsky, J.L., Giampapa, M.S.: 1987, presented at *Observational Astrophysics with High Precision Data*, eds. L. Delbouille, A. Monfils, Univ. of Liège, Liège, p. 103

Schmitt, J., Rosner, R., Bohn, H.: 1984, *Astrophys. J.* **282**, 316

Simon, T., Herbig, G., Boesgaard, A.M.: 1985, *Astrophys. J.* **293**, 551

Stauffer, J.R., Hartmann, L.W.: 1986, *Astrophys. J. Suppl.* **61**, 531

Steffen, M.: 1987, in *The Role of Fine-Scale Magnetic Fields on the Structure of the Solar Atmosphere*, eds. E.-H. Schröter, M. Vazquez, A.A. Wyller, Cambridge University Press, Cambridge, p. 47

Vilhu, O.: 1984, *Astron. Astrophys.* **133**, 117

Vilhu, O.: 1987, in *Cool Stars, Stellar Systems, and the Sun*, eds. J. Linsky, R. Stencel, Springer, Berlin, Heidelberg, New York, p. 110

Vilhu, O., Moss, D.: 1986, *Astron. J.* **92**, 1178

Vilhu, O., Gustafsson, B., Edvardsson, B.: 1987, *Astrophys. J.* **320**, 850

Vilhu, O., Walter, F.M.: 1987, *Astrophys. J.* **321**, 958

Vilhu, O., Linsky, J.L.: 1987, *Astron. J.* **99**, 1071

Vogt, S.S., Soderblom, D.R., Penrod, G.D.: 1983, *Astrophys. J.* **269**, 250

Walter, F.: 1986, *Astrophys. J.* **306**, 573