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CHROMOSPHERIC LINES IN RED DWARF FLARE STARS. I. AD LEONIS AND GX ANDROMEDAE

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ABSTRACT

Line profiles with a spectral resolution of 0.45 Å have been obtained for Hα(λ6563), the Na D lines (λλ5890, 5896), He I lines (λλ5876, 6678), and the Ca II infrared triplet lines (λλ8498, 8542, 8662) in the flare stars AD Leonis and GX Andromedae. The spectroscopic Reticon diode array observations of AD Leo were obtained simultaneously with high speed photometry, and major influences in the spectra due to flares are avoided by this technique. GX And has photospheric parameters very similar to AD Leo but shows a flare activity level more than one order of magnitude smaller. Simultaneous photometry was not done during spectroscopic observations of GX And because of the small probability that a flare should contaminate the data.

Despite apparently equal physical parameters at the photospheric level, the chromospheric lines observed in this program appear very different in AD Leo and GX And. Hα is a prominent emission line in AD Leo with a central absorption, for which the two peaks are separated by 0.6 Å. The FWHM of the line itself is 1.35 Å in AD Leo. In contrast, the Hα line in GX And is an absorption feature with FWHM=0.75 Å. The strength of this line is too large to be formed purely in the photosphere because temperatures are so low in this region that it is transparent to Hα and consequently forms only a very weak Hα absorption line. A collisionally dominated line may strengthen its absorption feature in a chromosphere before turning into emission (Cram and Mullan), and this is probably what is seen in GX And.

An emission feature in the blue wing of Hα in AD Leo, 20% above the continuum, is found to be present also in two nonflaring M dwarfs with Hα in absorption, and is associated with less TiO blanketing at that wavelength.

The Na D lines are broad absorption features in both stars with equal intensity distributions in the outer wings, reflecting the similarity of photospheric conditions in these stars. In AD Leo, however, the cores of the lines are seen in emission, the D_2 feature being stronger than D_1. These emission cores are unresolved at our resolution, but have a stellar origin. Also, in AD Leo the He I λ5876 line is detected clearly in emission, but the λ6678 line is much weaker. The filling-in of a Fe I absorption line by emission in this He I line is discussed, and the flux ratio of the λ5876 to λ6678 lines is not believed to give a correct triplet-to-singlet ratio for He I unless correction for the filling-in of the Fe I line is performed. In GX And none of the He I lines are detected, neither in emission nor absorption.

The Ca II infrared triplet lines are resolved for the first time in flare stars. In GX And, all three lines are seen in absorption. In the flare active AD Leo, however, the lines are found to be heavily filled in by emission, and only weak remnants of the absorption features remain. A central emission is present in the cores of the lines, but these features are unresolved at our spectral resolution. The central intensity is largest at the λ8498 line, which is the least opaque of the triplet lines. This sharply contradicts an optically thin formation of the lines and leaves an intriguing modeling problem.

Subject headings: stars: chromospheres — stars: flare — stars: individual — stars: late-type

I. INTRODUCTION

Flare stars comprise a subset of the solar neighborhood sample of red dwarfs. They cover the spectral types dK2e–dM6e (Pettersen 1976). All flare stars show Ca II H and K lines in emission. Most flare stars also show the hydrogen Balmer lines in emission and the most flare active are the ones with the strongest emission lines (Pettersen 1975). Only a few stars with exceptionally low flare activity levels (e.g. SZ UMa, GX And) show Hα in absorption.

Pettersen (1980*a*) studied three dozen flare stars (single stars and individual components in multiple systems) with respect to their physical parameters in the quiescent state. He determined the effective temperature, bolometric luminosity, and radius of each of these stars and concluded from a comparison with theoretical models that solar neighborhood flare stars are main sequence stars. Models of low mass dwarfs show that flare stars have deep convection zones. Although mass determinations are few, the lowest luminosity flare stars ($\log L/L_{\odot} \lesssim -2.5$) may never develop a radiative core and may thus be fully convective during their main sequence state.

Photoelectric photometry of several flare stars in their quiescent phase has revealed cyclic variations at the 10% intensity level. The generally accepted interpretation is that the flare star photosphere has a starspot or a dominating starspot group and that the appearance and disappearance of this spot due to the star's rotation modulates the magnitude in accordance with the rotation period. Slightly more than a dozen of the 70-odd known flare stars have been observed to be variable outside of flares, and even fewer are well enough observed for a period determination to be made. From existing data on single flare stars the equatorial rotation velocity is found to be 5–20 km s^{-1}. The most rapid rotator is a member of a spectroscopic binary where the rotation is synchronous to the orbital motion, and a rotational velocity of 40 km s^{-1} is found (YY Gem). An example of a slow flare star rotator is the single dM 4.5e star EV Lac, for which Pettersen (1980*b*) determined an equatorial rotation velocity of 4.2 ± 0.5 km s^{-1}.

It appears that solar neighborhood flare stars are strongly or fully convective dwarfs that rotate faster, up to an order of magnitude faster, than the Sun. Even though the source of chromospheric heating in the Sun has not yet been identified with certainty, one may assume that convection is important to the process. The existence of active chromospheres in flare stars is implied, and one may even ask if the convection and rapid rotation themselves are the ultimate cause of flare activity and of the higher flare incidence in red dwarfs than in other stars through generation of local magnetic fields on the stars.

We believe that the study of flare star chromospheres, where the physical conditions may be significantly different from those in the solar chromosphere, may help our understanding of the physics of this interesting part of a stellar atmosphere. It will also prove extremely important to know the conditions in a flare star chromosphere once a detailed modeling of the different aspects of the complex flare phenomenon itself is undertaken.

Using equipment available to us at McDonald Observatory, we have observed several spectral features believed to reflect the existence of a stellar chromosphere. Among the flare stars we have observed both active stars with a high flare incidence and stars which flare only rarely. Some stars are single field stars, and some are members of binary systems. The present paper is devoted to a presentation of our observational results for the active flare star AD Leo and the low activity flare star GX And.

The features observed by us in AD Leo with the exception of the Ca II infrared triplet lines were observed with a different instrument by Giampapa *et al.* (1978). This paper may serve as a comparison with regard to detectability, measurement precision, and chromospheric diagnostics.

II. THE STARS

AD Leo = Gliese 388 is an active flare star with apparent visual magnitude 9.43. There is no sign of variability in its radial velocity, and the suspected unseen companion (Reuyl 1943) was not confirmed in a detailed astrometric study by Lippincott (1969). The star is apparently single, and Pettersen (1980*a*) determined its physical parameters as $T_{\rm eff} = 3450$ K, $\log L/L_{\odot} = -1.621 \pm 0.004$, and $R/R_{\odot} = 0.44 \pm 0.05$. Using the mass-luminosity relation of Grossman, Hays, and Graboske (1974) we may estimate a mass of $0.44\ M_{\odot}$ for AD Leo, which leads to a surface gravitation $g = 6.23\ 10^4$ cm s^{-2} ($\log g = 4.79$ cgs).

A photometric study of the flare activity of AD Leo by Coleman and Pettersen (1981) concluded that the observed flare incidence and energy released matched the expected rate as estimated from a statistical relation for active flare stars (Lacy, Moffett, and Evans 1976). This relation probably represents an upper limit to flare activity as a function of stellar luminosity.

GX And = Gliese 15 A is a low activity flare star with an apparent visual magnitude 8.09. Joy (1947) suggested that it was a spectroscopic binary, but precise measurements show no radial velocity variations (Pettersen and Griffin 1980). The companion star is GQ And = Gliese 15 B, and the two apparently form a physical system with an orbital period of several thousand years. Pettersen (1980*a*) determined the physical parameters of GX And as $T_{\rm eff} = 3550$ K, $\log L/L_{\odot} = -1.618 \pm 0.004$, and $R/R_{\odot} = 0.41 \pm 0.05$. The dimensions and photospheric properties of AD Leo and GX And are therefore equal within the errors given.

Extensive photometric monitoring of GX And revealed that its flare activity is a factor of 26 lower than expected from the statistical relation (Pettersen and Griffin 1980).

The spectroscopic line profiles presented in this paper therefore refer to two stars with apparently equal photospheric conditions, but with highly different flare activity levels. There are striking differences in the chromospheric lines in these two stars.

III. INSTRUMENTATION AND OBSERVING PROCEDURE

Because AD Leo is known to flare about every $1\frac{1}{2}$ hours on the average in the ultraviolet (3600 Å), we considered it a necessity to collect the spectroscopic data together with information on the star's activity before and during the exposure. For this purpose we observed AD Leo simultaneously with two telescopes, one collecting photometric data and the other spectroscopic. The photometric flare monitoring of AD Leo was done by L.A.C., except during the one hour exposure on 1980 January 5 UT, when Gary Kern provided photometric coverage. All spectroscopic observations were done by B.R.P.

GX And flares so rarely and with such small amplitudes that we considered it unnecessary to have simultaneous photometry during the spectroscopic observations of this star. No flare activity was noted visually by the spectroscopic observer.

a) *Photometry*

The photoelectric observations were made with the 0.91 m reflector at McDonald Observatory and with a two channel high speed photometer controlled by a NOVA computer (Nather 1973). The main channel was used to monitor AD Leo through a *U* filter with a time resolution of one second. The second channel monitored a nearby comparison star at the same time resolution. One could therefore tell in real time whether a flare occurred on AD Leo, and the spectroscopic observer would be notified within seconds.

The photometric data were stored on magnetic tape and were later reduced on the CDC 6600 computer of the University of Texas at Austin.

b) *Spectroscopy*

The spectroscopic observations were made with the 2.1 m and 2.7 m reflectors at McDonald Observatory and their coudé spectrographs. The detectors were Reticon diode arrays cooled by liquid nitrogen (Vogt, Tull, and Kelton 1978).

The 2.1 m detector has 1728 elements. The part used for recording the stellar spectrum covers about 240 Å. We selected an entrance slit width of 90 μm which projects to three diodes on the detector. The spectral resolution on the 2.1 m scans is 0.45 Å, which is confirmed from the half-widths of lines in comparison spectra.

The 2.7 m detector has 1024 elements. The part used for recording the stellar spectrum covers about 90 Å. An entrance slit width of 440 μm projects to four diodes on the detector. The spectral resolution on the 2.7 m scans is 0.40 Å.

Typical integration times were 2–3 hours on AD Leo and about 1 hour on GX And (see observing log in Table 1). After the stellar spectrum had been recorded and the sky background was subtracted, a spectrum of a flat spectral lamp was obtained. The stellar spectrum was divided by this flat field spectrum to minimize pixel-to-pixel variations in the instrument. These data were considered our raw data and were stored on punched cards for further reduction at the CDC 6600 computer in Austin.

c) *The Observing Procedure*

Our aim was to obtain spectra of the quiescent flare stars. Since our spectral features are between λ5800 and λ8700 the influence of a small or medium flare on the continuum would be infinitesimal due to the low flux of the flare continuum at these wavelengths and the short lifetime of the continuum emission in a stellar flare. Besides, the *U* filter monitors mostly the behavior of the flare continuum, and this part of a flare could be avoided in our spectra by communication between the two observers.

More troublesome is the unknown influence on the chromospheric lines after the photometric flare is over.

TABLE 1

OBSERVING LOG: SPECTROSCOPY

Star	Date (UT)	Start (UT)	Effective Integration Time (minutes)	Feature	Remarks	Telescope
AD Leo......	1979 Apr 7	06 17 08	172	Na I D, He I	No flares	2.1 m
AD Leo......	1979 Apr 8	03 30 50	100	Ca II IR	No flares	2.1 m
AD Leo......	1979 Apr 9	04 12 29	120	Hα	No flares	2.1 m
AD Leo......	1979 Apr 10	03 59 35	103	Na I D, He I	3 flares	2.1 m
AD Leo......	1979 Apr 12	03 56 00	149	Hα, He I	3 flares	2.1 m
AD Leo......	1979 May 9	02 28 33	116	Ca II IR	3 flares	2.1 m
AD Leo......	1979[a] May 11	02 20 37	104	Ca II IR	4 flares	2.1 m
AD Leo......	1980 Jan 5	10 41 56	53	Hα	1 flare	2.7 m
Gliese 411 ...	1980 Jan 5	09 58 29	30	Hα	...	2.7 m
Gliese 526 ...	1980 Jan 5	11 52 34	33	Hα	...	2.7 m
GX And	1979 Sep 8	08 28 00	80	Ca II IR	No flares	2.1 m
GX And	1979 Sep 8	10 28 55	60	Hα	No flares	2.1 m
GX And	1979 Sep 9	08 32 12	45	Na I D	No flares	2.1 m

[a] This spectrum was obtained with twice the usual slit width. The spectral resolution is 0.9 Å.

We had no way of monitoring that effect. There is surprisingly little difference, however, between spectra of the same feature that were obtained with no flare influence and those obtained with several flares interrupting the observations. The explanation may be that a long integration of several hours masks out the influence of short time flares.

The standard observing procedure was as follows.

The photometric telescope would begin monitoring the flare star and continue to do so for about one hour. If the observer was certain that the star was at its quiescent level, the spectroscopic telescope would be pointed at the flare star and the integration would begin.

Both observers would be connected by open line telephone from then on, and they could communicate readily.

If the photometric observer noticed an increase in the signal from the flare star exceeding the standard deviation of the noise or more, he would immediately notify the spectroscopic observer who would close the shutter of the spectrograph and record dark current. Results from several incidents of this kind show that the shutter was closed 15 seconds (or earlier) after the flare signal increased above the agreed level. By this time the photometric observer would have had time to inspect the signals from both the flare star and the comparison star. In the case of false alarm (due to transparency variations, etc.) which would show in both channels, the spectroscopic observations would commence. If a flare really did occur, the spectrograph would sit idle until the photometric observer considered the flare star intensity to be back to normal. Then the spectroscopic observations would resume.

When the spectroscopic observer considered the effective integration time sufficient, the signal was read out and temporarily stored in the computer.

IV. OBSERVATIONAL RESULTS

The spectral region available to us was governed by the response of the Reticon and the spectral types of the stars on the program. Flare stars are cool stars with the maximum of their energy distributions near 1 μm. The Reticon detector loses sensitivity rapidly towards the blue part of the spectrum. Thus the commonly used chromospheric indicators, the Ca II H and K lines, were not accessible with our instrument. We have selected spectral features between λ5800 and λ8700 to optimize detector sensitivity and the flux from these red dwarfs. In this section we will present the results for each of the spectral features selected for this program. Table 1 gives a detailed observing log for the data presented.

Because of the low photospheric temperature of the stars, all spectral regions observed are influenced by molecular absorption bands. It is not clear where the continuum level is. The best we can do is to define as thoroughly as possible the position of the local continuum, using the whole 240 Å range of the 2.1 m spectra. To do this we compare the star in question with a very high signal-to-noise spectrum of ε Eri or 61 Cyg A. These stars have spectral type K2 and do not show the molecular features. The continuum is therefore easier to define, and a direct comparison between these stars and the flare star defines the local continuum over the 240 Å region. The low signal-to-noise ratio for some of the spectra introduces its own uncertainty in the definition of the continuum.

The wavelength scale was established by using absorption lines over the whole 240 Å region. Hence wavelengths are in the stars' rest frames.

Data on emission features seen in AD Leo are given in Table 2, and the measured quantities for absorption features in the stars observed are given in Table 3.

a) *The* Hα *Emission Line*

We have obtained spectra of the Hα emission feature in AD Leo at three different dates (see Table 1). The two recordings obtained during 1979 April were taken at two different grating angles with the same instrument so that a different set of diodes on the linear Reticon detector was employed to record the emission line pro-

TABLE 2

SPECTROSCOPIC QUANTITIES FOR EMISSION FEATURES IN AD LEO

Feature	Wavelength (Å)	Equivalent Width (Å)	FWHM (Å)	Central Intensity[a]	Remarks
Hα	6563	3.03	1.38	3.02	1979 Apr
Hα	6563	3.15	1.36	3.24	1980 Jan
He I.......	5876	0.22	0.66	1.01	
Na D_1	5896	0.08	0.46	0.44	
Na D_2	5890	0.12	0.43	0.53	
Ca II	8498	0.10	0.52	1.05	
Ca II	8542	0.10	0.52	1.01	
Ca II	8662	0.10	0.73	0.84	

NOTE—The footpoints of the emission cores in the Ca II infrared lines in AD Leo are 0.85 (λ8498), 0.78 (λ8542), and 0.70 (λ8662).

[a] Relative to the local continuum.

TABLE 3

SPECTROSCOPIC QUANTITIES FOR ABSORPTION FEATURES

Feature	Wavelength (Å)	Star	Equivalent Width (Å)	FWHM (Å)	Central Intensity[a]	Remarks
Hα	6563	GX And	0.32	0.72	0.40	
Hα	6563	Gl. 411	0.40	0.74	0.44	
Ca I	6572	AD Leo	0.33	0.63	0.50	1979 Apr
Ca I	6572	AD Leo	0.36	0.70	0.47	1980 Jan
Ca I	6572	GX And	0.30	0.61	0.42	
Ca I	6572	Gl. 411	0.29	0.55	0.48	
Ca II	8498	AD Leo	0.42	...	0.85[b]	
Ca II	8498	GX And	0.66	0.88	0.57	
Ca II	8542	AD Leo	0.95	...	0.76[b]	
Ca II	8542	GX And	1.85	1.69	0.38	
Ca II	8662	AD Leo	0.79	...	0.65[b]	
Ca II	8662	GX And	1.40	1.41	0.40	

[a]Relative to the local continuum.

[b]The central intensities for the Ca II infrared triplet lines in AD Leo are given as the point of deepest absorption recorded. This point is not at the central wavelength of the line, due to the presence of core emission.

file during these two exposures. The spectrum of 1979 April 9 UT was obtained without any interruptions of flares and thus clearly represents the Hα emission profile of the quiescent star at that date. The Hα profile obtained three nights later is remarkably equal to the first profile, although the exposure was interrupted three times by flares. The two profiles are shown in Figure 1. We can only suggest that the Hα emission contribution of the flares decayed relatively rapidly, as we resumed spectroscopic integration a few minutes after each of the flares returned to preflare intensity levels as measured through the U filter. Also, the time spent on an apparently quiescent star is longer than the time over which it is believed to have shown persistent flare emission in the lines, and so this integration effect may have masked out any influence from the later part of the flares.

Since the two Hα emission profiles are so nearly identical, we have averaged the two spectra of 1979 April to obtain a better signal-to-noise ratio for more certain line identifications. In Figure 2 we show a 25 Å portion around Hα, with atomic lines identified. Also, along the two horizontal axes, there are positions of telluric water vapor lines and of stellar TiO lines that may contribute to the appearance of the spectrum of AD Leo. In fact, there are weak lines and blends associated with all the positions for TiO lines.

Two features are distinctly noticeable in the Hα emission profile. The first is the central absorption evident in all spectra obtained of AD Leo. Many other flare stars

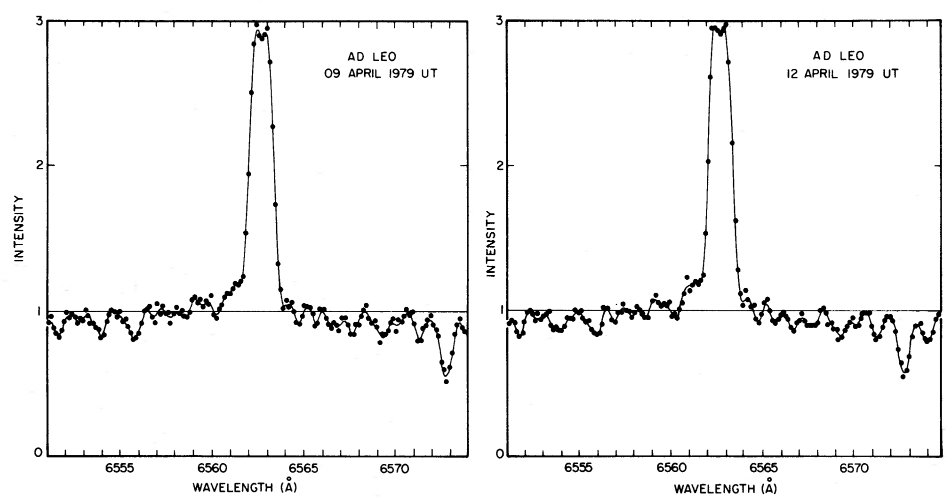

FIG. 1.—The Hα emission line profiles of AD Leo obtained on two different nights. The spectrum to the left was taken without any interruption from flare activity, while the one to the right was interrupted by three flares. The two spectra are identical within measurement errors.

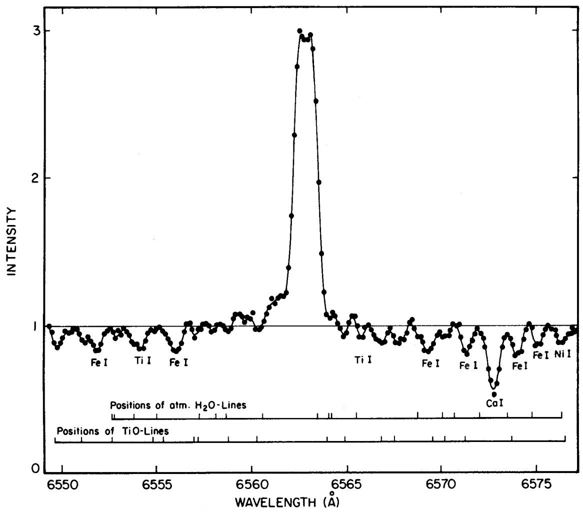

FIG. 2.—The averaged Hα profile of AD Leo. Atomic lines are identified. The positions of telluric water vapor lines and stellar TiO lines are shown along the two horizontal scales. The central absorption feature and the blue asymmetry of the Hα profile near continuum is discussed in the text.

also show this feature. It was first observed in several active flare stars other than AD Leo by Worden and Peterson (1976), who concluded that the Hα emitting region must be optically thick. They also argued that the width of the Hα emission profile implies an electron density less than 10^{13} cm^{-3}. From our spectra we determine FWHM$=1.35$ Å, which is consistent with Giampapa *et al.* (1978) who found a value of 1.4 Å in AD Leo. The profiles in Worden and Peterson (1976) have FWHM≈ 1.2 Å for three other flare stars.

In a red dwarf flare star the temperature minimum of the atmosphere is so cold (2200–3200 K) that it is transparent to Hα. The photosphere itself emits a very weak Hα absorption line. For electron density larger than 10^{11} cm^{-3} the line source function is collisionally dominated (Fosbury 1974; Cram and Mullan 1979). The Hα line is therefore a sensitive chromospheric diagnostic in flare stars, and it appears in emission if the chromosphere has sufficient optical depth. The strength of the emission is proportional to the cube of the electron density, but it also depends on the effective temperature of the star and the temperature in the chromosphere (Cram and Mullan 1979). The line source function increases inwards as the square root of the line center optical depth to a maximum value and then decreases symmetrically. Therefore the emission line shows a central absorption. The separation of the two peaks depends only slowly on the chromospheric optical depth (Cram and Mullan 1979), and differences from star to star would still lead to about the same separation. For AD Leo we determine a separation of the two peaks of 0.6 Å.

The second noticeable feature of the Hα emission profile is the asymmetry of the line close to continuum. To the blue there is an emission component visible in both spectra obtained in 1979 April (Figs. 1 and 2) with different grating settings, so the feature is not instrumental in origin. The emission reaches a maximum about 20% above the continuum level and stretches out about 1.3 Å to the blue of Hα itself. The feature is visible in some other flare stars if their spectra are recorded with a sufficient signal-to-noise ratio. A first guess is that we are detecting a velocity field in the lower chromosphere of AD Leo with consistently outward motion of velocities up to 60 km s^{-1}. The feature appears at a position where there are no TiO absorption

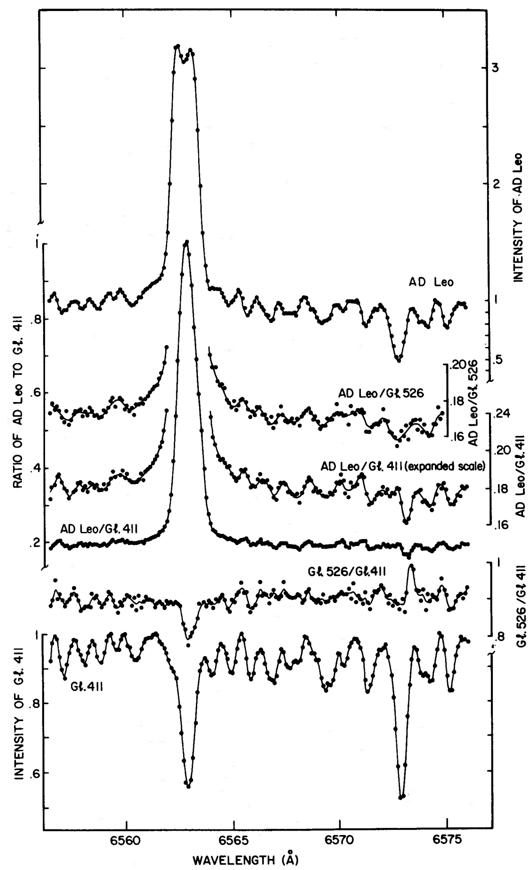

FIG. 3.—Comparison of the Hα feature in AD Leo with nonflaring M-dwarfs. The upper and lower panels show the Hα profiles of AD Leo and Gliese 411, respectively, obtained on 1980 January 5 UT. The second panel from the top shows the result of a division of the spectrum of AD Leo with that of Gliese 526, a nonflaring M-dwarf. The next two panels show the results when divided with the spectrum of another nonflaring M-dwarf, Gliese 411. Below this is a panel showing the spectrum of Gliese 526 divided with the spectrum of Gliese 411. The dip at Hα results because Gliese 526 has a slightly deeper absorption than Gliese 411. The asymmetry of the Hα profile near the continuum is seen in both AD Leo and Gliese 411 and disappears when the spectrum of one star is divided with that of another of similar spectral type.

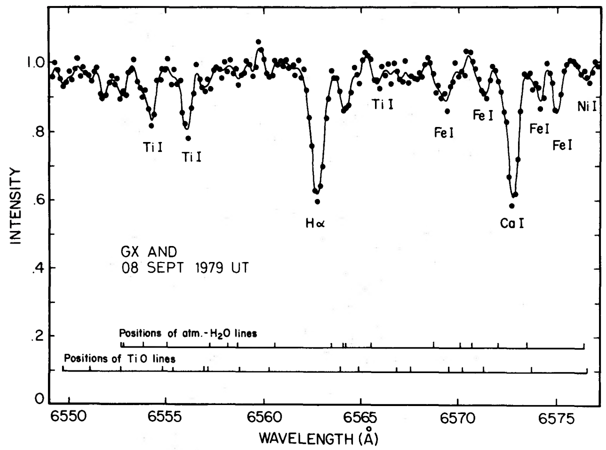

FIG. 4.—The Hα absorption line in GX And. Atomic lines are identified. The positions of telluric water vapor lines and stellar TiO lines are shown along the two horizontal scales.

lines, however, and this suggests that the emission actually represents a level closer to the real continuum and that the surrounding local continuum is suppressed by numerous TiO absorption lines.

We have reobserved AD Leo in 1980 January with the 2.7 m telescope, and with the same instrumental setup we have also recorded the Hα spectra of two absorption line nonflaring M dwarfs of about the same spectral type as AD Leo, Gliese 411 and Gliese 526. These spectra have better signal-to-noise ratios than the previous ones.

The Hα emission in AD Leo was only a few percent stronger than in 1979 April. The central absorption is clearly visible with a separation of the two peaks of 0.6 Å. The FWHM (Hα) is 1.35 Å. The blueshifted emission is present with an intensity of 20% above the continuum and stretching out to about 1.1 Å.

A close inspection of the spectra of Gliese 411 and 526 shows that the blue wing of Hα has higher intensity than the red close to continuum. The red wing is influenced by TiO lines. Figure 3 shows portions of the spectra of AD Leo and Gliese 411.

The AD Leo spectrum was divided, diode per diode, with the absorption line spectra of Gliese 411 and 526, respectively. Figure 3 shows the ratios of the divisions Gliese 526/Gliese 411, AD Leo/Gliese 526, and AD Leo/Gliese 411. It is evident that the asymmetry disappears in the divided spectra, which suggests that molecular features are responsible for it, and that the presence of these features in stars of approximately the same temperature will disappear when the spectrum of one star is divided by that of another.

Figure 4 shows a 25 Å portion of the spectrum of GX And and reveals Hα in absorption. The line is narrow, with FWHM=0.75 Å. There is no emission component visible blueward of Hα, but the TiO lines in the red wing of Hα can be identified with blends of atomic lines.

b) *The* Na I *D lines*

The Na D lines are believed to furnish information about the physical conditions in the lower chromosphere and upper photosphere. These lines are therefore potentially important for the study of the temperature minimum in a flare star chromosphere.

Two spectra are available of the Na I D lines (λλ5890, 5896) in AD Leo, both obtained with the 2.1 m telescope. The first spectrum was obtained without interruptions due to flaring, whereas the second recording was interrupted by three flares. A direct comparison of the two spectrograms again shows no measurable difference between them to the noise level we have obtained, and both recordings are averaged to improve the signal-to-noise ratio. The result is shown in Figure 5. The Na D lines are characterized by broad wings and deep absorption. The core of the lines show reversals and go into emission. The D_2 line appears to be the stronger of the two. The emission cores are unresolved at our resolution of 0.45 Å. This is consistent with the observations of other flare stars by Worden and Peterson (1976) that the emission cores are unresolved at 0.2 Å in their spectra. We consider the origin of the emission to be stellar since McDonald Observatory is not influenced by artificial light sources and is considered to be a dark site. Giampapa *et al.* (1978) also concluded that the emission was stellar. The presence of several molecular band heads and numerous molecular lines over the 240 Å of spectral data makes it very difficult to determine the position of the continuum. A local continuum has been fixed from a comparison with the spectrum of hotter K2 dwarfs, where the molecular features are not dominant.

Figure 5 also presents the Na D region in GX And. The outer wings approach the continuum level in the same manner as in AD Leo, and this confirms that the two stars have close similarities in physical parameters near their photosphere regions. In GX And, there is no sign of emission cores in either of the two D lines, and the upper panel of Figure 5 shows the result of a division pixel-by-pixel by the AD Leo spectrum with that of GX And. This flux ratio plot shows excess emission in AD Leo relative to GX And even several Å from the line center, especially in the more opaque D_2 line.

c) *The* He I *Lines*

Also included in Figure 5 is the symmetric profile of the He I triplet line λ5876, in emission in AD Leo. It is evident on both spectrograms of this spectral region of AD Leo, and there is no detectable difference in strength between the nonflare spectrum and the recording that

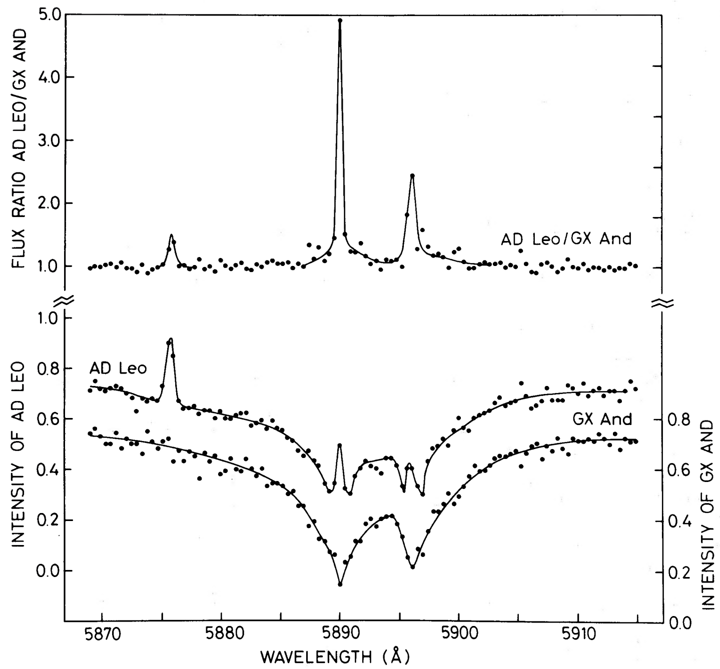

FIG. 5.—The Na D line region in AD Leo and GX And. The spectrum of GX And was obtained on 1979 September 9 UT, whereas the AD Leo spectrum is the average of two exposures, on 1979 April 7 UT and 1979 April 10 UT. The cores of both D lines show a narrow, unresolved emission in AD Leo, but not in GX And. The outer wings in both stars have equivalent distributions. In AD Leo the λ5876 triplet line of He I is prominently in emission. In GX And, no line is visible at this wavelength. The upper panel shows the flux ratio of AD Leo to GX And, normalized to continuum.

was interrupted by three flares. The averaged spectrum of AD Leo in Figure 5 therefore gives a representative profile for the He I D_3 line. We determine a FWHM of 0.6 Å.

Measured relative to the "continuum" value in the Na D_2 wing near λ5876, we find E.W. = 0.38 Å. Compared to the results of Giampapa *et al.* (1978), who found E.W. = 0.31 Å, this argues in favor of little or no variability in the λ5876 He I flux. The equivalent width of the Hα emission changed from 4.4 to 3.0 Å over the same interval of time.

GX And shows no sign of either emission or absorption at the λ5876 position. The He I D_3 line is not detected in this flare star.

The subordinate He I λ5876 line may be excited by a coronal XUV radiation field and, as such, may monitor the corona, rather than the chromosphere. It may also be formed by collisions, so it is not clear what the message from this line is.

One spectrum of AD Leo obtained on 1979 April 7 UT with no flares interrupting the integration includes a spectral region red enough to include the He I singlet line λ6678.1. In Figure 6 a weak emission feature is visible at the λ6678 position, and Giampapa *et al.* (1978) identified this as the He I line. Inserted also in Figure 6 is a portion of a spectrum of 61 Cyg B (dM0) at that wavelength, which shows a Fe I absorption line at λ6678.0. The feature at λ6678 Å may very well be the He I singlet in emission, but the emission flux measured will have to be corrected for the filling-in of the Fe I line, an absorption feature seen in all nonflaring M dwarfs we have observed. To obtain their fluxes and study the triplet-to-singlet ratio for He I, Giampapa *et al.* (1978) did not correct for the presence of the photospheric Fe I line. Besides, the λ6678 line is close to TiO band heads, and it is difficult to establish the correct position of the continuum. Again we have determined the local continuum from comparison with K2 dwarfs. We therefore offer a word of caution about the λ6678 singlet line and suggest that the He I triplet-to-singlet ratio may not be as easily accessible as first thought. The use of a Planck function to estimate continuum fluxes in regions where heavy molecular blanketing is evident, as done by Giampapa *et al.* (1978), is also highly questionable.

Figure 6 also shows the same portion of the spectrum for GX And. At the λ6678 position a weak absorption line is visible. It is impossible to decide if this is the Fe line partly filled in by the He I emission, but the absorption feature is clearly weaker in GX And than in 61 Cyg B. We can safely state that no He I emission above local continuum is seen in GX And.

d) The Ca II *Infrared Triplet Lines*

The results presented for the Ca II infrared triplet region in AD Leo will be based on a spectrum obtained

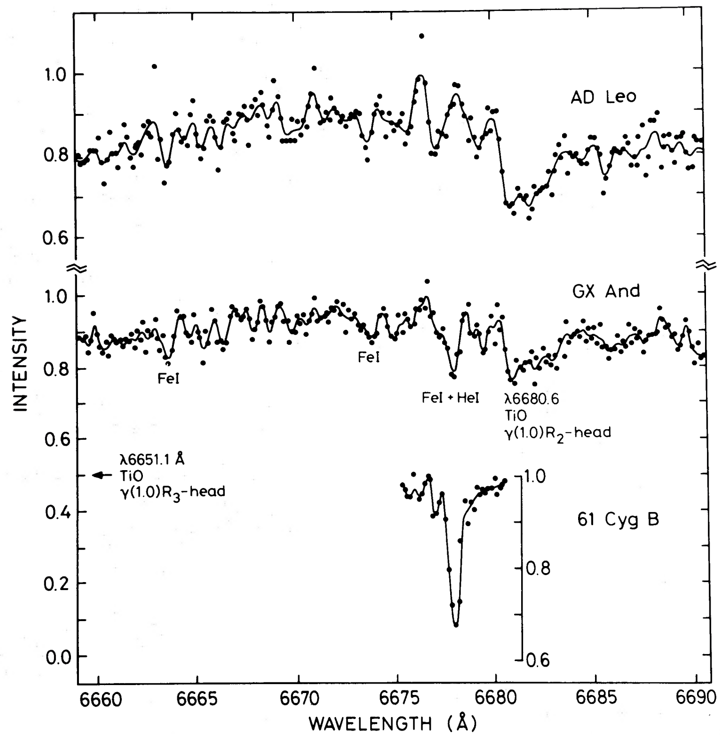

FIG. 6.—The spectral region around the He I λ6678 line in AD Leo (1979 April 12 UT) and GX And (1979 September 8 UT). Major molecular features are identified. The λ6678 line is seen weakly in emission in AD Leo. In GX And, a shallow absorption feature is found at this wavelength. Also inserted is the Fe I absorption line in 61 Cyg B, a dM0 nonflaring dwarf. The profile of the He I line is evidently blended by the Fe I line. The use of the He I λ6678 line for determination of the He I singlet-to-triplet ratio is discussed in the text.

with the 2.1 m telescope on 1979 April 8 UT, a recording with no interruptions due to flares. Two spectra were also obtained in May 1979, but they were of low signal-to-noise ratio or had low spectral resolution, so they will not be discussed here.

The 2.1 m Reticon detector proved excellent for an observational study of the Ca II infrared triplet lines. It has enough diodes to cover a spectral range of about 240 Å, which is enough to include all three lines (λλ8498, 8542, 8662) in the same exposure. In our program all three lines are observed simultaneously.

The Ca II infrared triplet lines are collisionally dominated subordinate lines and respond to a change in chromospheric density or structure by a change in core intensity. These lines couple the 4 ^2P states, the upper states of the Ca II H and K lines, with the 3 ^2D metastable states. They are less opaque than the H and K lines. The λ8542 line is the most opaque of the triplet lines and is nine times as opaque as λ8498, the least opaque member, with which it shares the upper state. The ionization of Ca I occurs deep in the atmosphere and a steep chromospheric temperature gradient would contribute to a bright core in the triplet lines.

Figure 7 shows the spectral region around the λ8498 line. The deep and broad absorption line seen in nonflaring M dwarfs is also seen in GX And. The FWHM is 0.9 Å in this star. In AD Leo, however, the line is strongly filled in by emission, and a weak emission core is present. The FWHM of the visible part of this emission is 0.5 Å. The flux at the line center of λ8498 Å in AD Leo is comparable to the nearby continuum flux and is 1.8 times as strong in AD Leo as in GX And, measured relative to their respective continua.

Figure 8 shows the λ8542 line. Considerably more of the outer wings is detected in this line in AD Leo, but there is still heavy filling-in by emission relative to what is seen in GX And. A distinct emission core appears at line center with FWHM=0.45 Å. The line center flux in AD Leo is very close to the continuum level. Measured relative to their respective continua, the line center flux in AD Leo is 2.4 times that of GX And for the λ8542 line.

Figure 9 shows the λ8662 line. The outer wings in AD Leo are well defined, but the inner wings are again filled in by emission as compared to the profile of GX And. A somewhat noisy signal makes the appearance of the emission core less clear, but we consider the profile strongly indicative of an emission core. The FWHM is close to the instrumental resolution.

The flux ratio plot shows a line center flux in AD Leo which is 2.1 times that of GX And, measured relative to their respective continua.

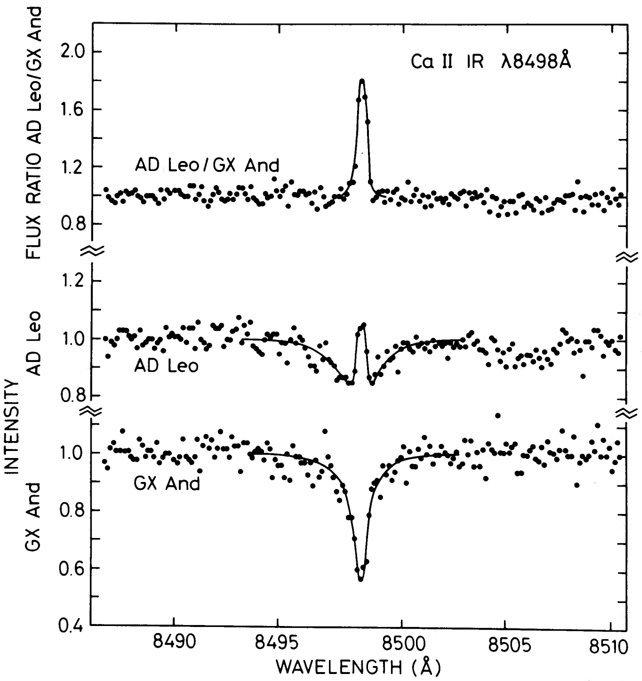

FIG. 7.—The Ca II λ8498 line in AD Leo (1979 April 8 UT) and GX And (1979 September 8 UT). None of the stars flared during the exposures. The distinct absorption feature seen in GX And is partially filled in by emission in AD Leo, and a central emission core is visible. The upper panel shows the flux ratio of AD Leo to GX And, normalized to continuum.

We therefore reach the rather surprising observational result that the center intensity as measured relative to the local continuum is strongest for the λ8498 line, a little weaker for the λ8542 line, and distinctly weakest for the λ8662 line in AD Leo. In GX And, λ8498 also has the brightest core, but the two other lines have equal central intensities. In both stars the absorption feature of λ8542 has the largest equivalent width among the Ca II triplet lines, and the smallest equivalent width is found in the λ8498 line. This relates to the fact that the FWHM of the absorption features are largest in the λ8542 line and about twice as small in λ8498. The least opaque among these lines is the λ8498 line, whereas the most opaque is the broad one, λ8542.

In an optically thin gas, the ratios of the fluxes emitted in the three Ca II infrared triplet lines scale according to their opacities, i.e., 8498:8542:8662 = 1:9:5. This is not observed in any red dwarf star, whether a flare star or not. The conclusion must therefore be that the Ca II infrared triplet lines are formed in an optically thick medium.

By studying the behavior of the triplet lines in the quiet solar chromosphere, in plage regions of different brightness, and in solar flares, Shine and Linsky (1974) and Machado and Linsky (1975) found that a steepening temperature gradient in the line formation region would explain the behavior of the lines. This is because ionization of Ca I occurs at large depths in the atmosphere, and the temperature, electron density and Ca II

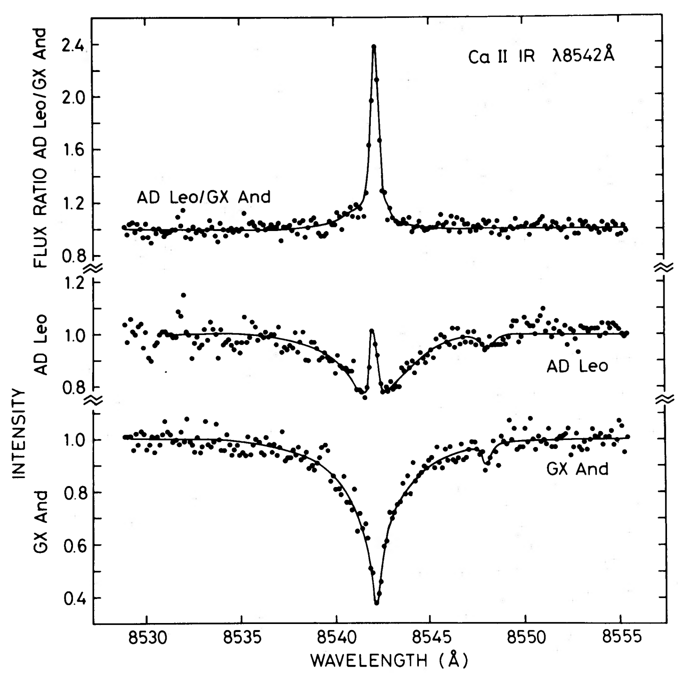

FIG. 8.—The Ca II λ8542 line in AD Leo (1979 April 8 UT) and GX And (1979 September 8 UT). None of the stars flared during the exposures. The broad absorption feature seen in GX And is partially filled in by emission in AD Leo, and a central emission core is visible. The upper panel shows the flux ratio of AD Leo to GX And, normalized to continuum.

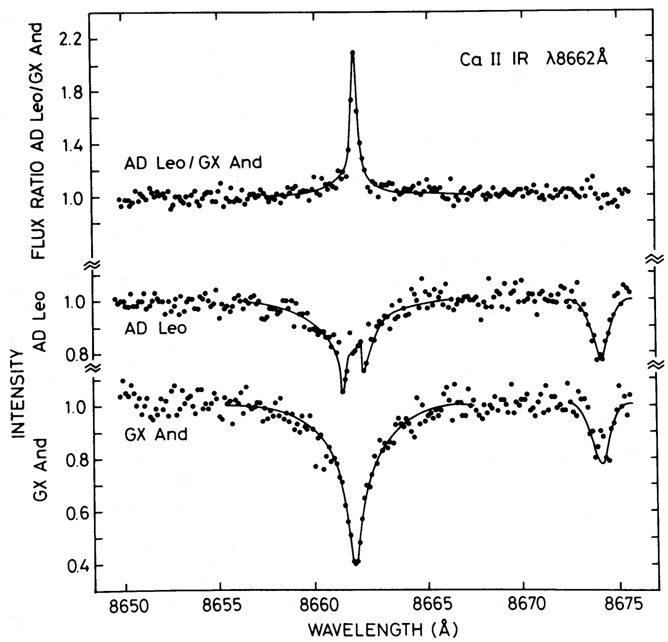

FIG. 9.—The Ca II λ8662 line in AD Leo (1979 April 8 UT) and GX And (1979 September 8 UT). None of the stars flared during the exposures. The broad and deep absorption feature seen in GX And is partially filled in by emission in AD Leo, and we believe a central emission core is visible. The upper panel shows the flux ratio of AD Leo to GX And, normalized to continuum.

density would increase at each line center optical depth, and thus produce brighter cores in the Ca II infrared triplet lines. The models constructed for the solar considerations do not explain directly the line ratios observed in the flare stars AD Leo and GX And, however. We notice that the considerations by Cram (1979) in a study of T Tauri star chromospheres will not lead to the ratio observed in flare stars, either. It is possible that a model would have to account for the inhomogeneity of the source in order to arrive at a satisfactory agreement with observations. In particular, theorists will face a difficult problem in explaining why the least opaque line has the strongest line center flux. Cram (1979) suggested that a selective excitation mechanism may be operating in an optically thick chromosphere, but the identity of this mechanism still remains unknown.

V. DISCUSSION

The lines selected for observation in flare stars were chosen with the intention of being useful diagnostics for the chromospheric structure of these stars. The spectroscopic finding for Hα, Na, and He I in AD Leo are consistent with observational results on the same star by Giampapa *et al.* (1978) and with results on other active flare stars obtained by Worden and Peterson (1976). The Ca II infrared triplet lines have not been observed previously in flare stars with resolution high enough to resolve the line profiles.

The comparison of AD Leo to GX And has demonstrated that two stars with equal dimensions and physical parameters in their photospheres may have distinctly different chromospheric properties as manifested through lines formed at these levels of the atmosphere. In particular, the observations have shown that GX And shows all the spectral features discussed in absorption, whereas AD Leo shows strong emission in Hα and He I λ5876 and narrow emission cores in the Na D and Ca II infrared lines. These differences are probably linked to the fact that AD Leo is a much more active flare star than GX And. Relative to the empirical relationship between the flare activity level of a star and its luminosity, established in a study of eight active flare stars by Lacy, Moffett, and Evans (1976), AD Leo is in its expected position (Coleman and Pettersen 1981), whereas GX And is less active by a factor of 26 (Pettersen and Griffin 1980).

Strong flare activity apparently goes along with an "active" chromosphere. The emission cores in the Ca II infrared lines and the strong emission in Hα in AD Leo indicate a steeper temperature gradient in this star than in GX And. This may be supported by the emission in the He I λ5876 line, but it is not clear to what extent emission in this line is influenced by extreme ultraviolet emission from a corona. A corona around the dM4.5e flare star YZ CMi was detected recently in X-rays (Pettersen *et al.* 1980). The narrow emission cores in the Na D lines in AD Leo indicate that the chromospheric temperature gradient extends quite deep towards the photosphere. If GX And has a chromosphere, it probably does not start as deep as in AD Leo, and the temperature gradient is smaller. The theoretical results by Cram and Mullan (1979) on the behavior of the Hα line in a chromosphere support the conclusion that both stars possess a chromosphere.

As these two stars have equal photospheric properties, the reason for the differences in flare activity and chromospheric structure must be a parameter not yet discussed here. From solar analogies we suggest that the availability of local magnetic field structures determines the result. This suggestion is of course speculative, but a reasonable working hypothesis is that the local magnetic fields on these stars are the results of an interplay between convection, which is very strong in red dwarfs, and the stellar rotation. If the depth of the convection zone depends only on the mass of the stars, as advocated in models of red dwarfs, then AD Leo should prove to be a more rapid rotator than GX And.

We have observed AD Leo and GX And photoelectrically on several occasions with the equipment and technique described in Pettersen (1980*b*). The measurements were made relative to nearby comparison stars. The purpose was to look for variations in the magnitudes of the stars due to the presence of photospheric starspots. If these could be detected, the equatorial rotational velocity of the stars can be determined (Pettersen 1980*b*). However, we could not detect any variations in either star with a measurement precision of typically 0.02 mag or better. Spots on flare stars change their sizes on a time scale of months, and very often no variation can be detected photometrically. Another try may therefore prove successful, although the possibility exists that one or both of the flare stars studied here are seen nearly pole-on.

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