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CHROMOSPHERES OF THE ACTIVE DWARF BINARIES EQ PEGASI AND ξ BOOTIS

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ABSTRACT

Ultraviolet spectroscopic measurements of the M dwarf binary EQ Peg and the G8 V star ξ Boo A have been made with the *International Ultraviolet Explorer* satellite. High-temperature emission lines (N V, C IV, Si IV) are present with similar strengths in both stars. The surface fluxes of chromospheric and transition-region lines are enhanced relative to those of normal main-sequence stars and are comparable to those observed in solar active regions. If inhomogeneities are present, the surface fluxes may be markedly higher than the derived values. It is likely that the emission observed from EQ Peg was not the result of major flare activity; however, the quiescent radiative losses observed in the ultraviolet are comparable to the time-averaged optical flare losses. The similarity of the line emissions of active dwarfs of diverse spectral types suggests that the character of the transition region is independent of the stellar effective temperature.

Subject headings: stars: chromospheres — stars: flare — stars: late-type — ultraviolet: spectra

I. INTRODUCTION

Many late-type dwarfs exhibit much higher levels of chromospheric activity than does the Sun. The most dramatic examples are the dMe stars, which undergo flares with energies considerably exceeding those of solar flares; however, there is a wide range of hotter dwarfs, with strong ionized calcium emission, for which optical detection of comparable flares would be extremely difficult. Because of the problem of contrast, and because the optical emission lines are generally produced in relatively low temperature regions, it is necessary to observe high-temperature lines in the ultraviolet in order to obtain a more complete picture of chromospheric activity.

In this *Letter* we present a spectroscopic observation of the double flare star EQ Peg (dMe + dMe) with the *International Ultraviolet Explorer* satellite (*IUE*), which was accompanied by optical monitoring during most of the exposure. The observed fluxes of ultraviolet lines are compared with similar data for ξ Boo A (HD 131156), an active G8 V star. The results suggest that there is very little difference in the behavior of transition-region lines among active dwarfs of different spectral types, and that active dwarfs have chromospheric structures more comparable to solar active regions than to the quiet Sun.

II. OBSERVATIONS

a) EQ Pegasi

EQ Pegasi (BC +19°5116) is a visual binary of separation $\sim 3''.7$ and $\Delta m = 2.0$ mag, with spectral types M3.5e V + M4.5e V using the corrections of Wing and Yorka (1979) to the types of Joy and Abt (1974). Owen *et al.* (1972) have established that both components undergo flares. The components have apparent magnitudes $V = 10.38$ and 12.4 and absolute magnitudes $M_V = 11.33$ and 13.4 (Gliese 1969). In all of our observations, both spectroscopic and photometric, both stars were included within the aperture.

EQ Peg was observed with *IUE* on 1978 December 16, from 00:10 to 03:10 UT, in one exposure (SWP 3612) with the large aperture in the short-wavelength, low-dispersion mode (1150–1950 Å, resolution 6 Å). Details of the instrument can be found in Boggess *et al.* (1978). Numerous emission lines are present in the spectrum (Fig. 1), which is discussed more fully in § III below. The strongly Lα line is mostly of geocoronal origin since it fills the $10'' \times 20''$ aperture; stellar Lα emission is present, but overexposed.

Simultaneously with the *IUE* exposure, EQ Peg was monitored photoelectrically in the Johnson *U* band with the 0.8 m (32 inch) telescope at Perkins Observatory in Delaware, Ohio. Observations were made with pulse-counting electronics and 10 s integration periods. The Moon was full, and the contribution of skylight to the *U* band signal varied from 67% at the beginning of the series, when EQ Peg was at air mass sec $z = 1.09$, to 89%, when observations ended at sec $z = 1.60$. The 1 σ scatter in the readings was about 9%. Photometry of EQ Peg is shown in Figure 2, where the contribution of skylight has been subtracted and the readings have been corrected for extinction amounting to 0.75 mag per air mass.

No obvious flares were recorded during this period. Most of the scatter in Figure 2 can readily be accounted for in terms of photon statistics and fluctuations in

[1] Guest Observer with the *IUE* satellite.

sky brightness. The three highest readings, which are 25–30% above the mean quiescent level, may be the result of real flares, but if so, these flares were relatively minor events of the "spike" variety, lasting not more than 10–15 s. Every second reading was recorded; however, twice as many readings were inspected as are shown in Figure 2, and there never occurred two consecutive 10 s readings that were 2 σ above the mean. The occurrence of two or three small flares would be consistent with the average behavior of EQ Peg: from Moffett's (1974) data, 1.8 flares (of any size) would be expected in this monitoring time.

The start of optical observing was delayed by clouds. With this delay and breaks for sky measurements, the ground-based coverage was 141 minutes during the 180 minute *IUE* exposure. We use Moffett's (1974) data to estimate a probability of $\sim$0.11 that a major flare of equivalent duration $\geq$3 minutes in U was missed during the observing breaks.

At the conclusion of the U band monitoring, three-color photometry of EQ Peg was obtained and reduced relative to a set of nearby standard stars. The results (for the combined light) are $V = 9.99$, $B - V = 1.54$, and $U - B = 0.91$; the uncertainty in $U - B$ is at least ± 0.10 because of the large contribution from the sky. The observed colors are reasonably consistent with the values $B - V = 1.56$, $U - B = 1.06$ reported in Gliese's (1969) catalog.

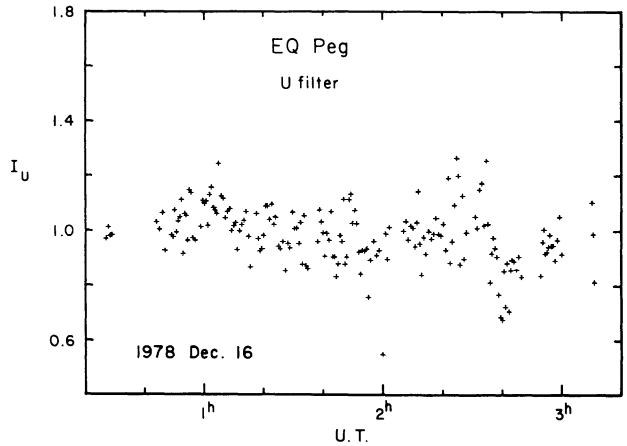

FIG. 2.—U band photometry of EQ Peg during the simultaneous *IUE* exposure. Flux measurements are normalized to the mean quiescent level.

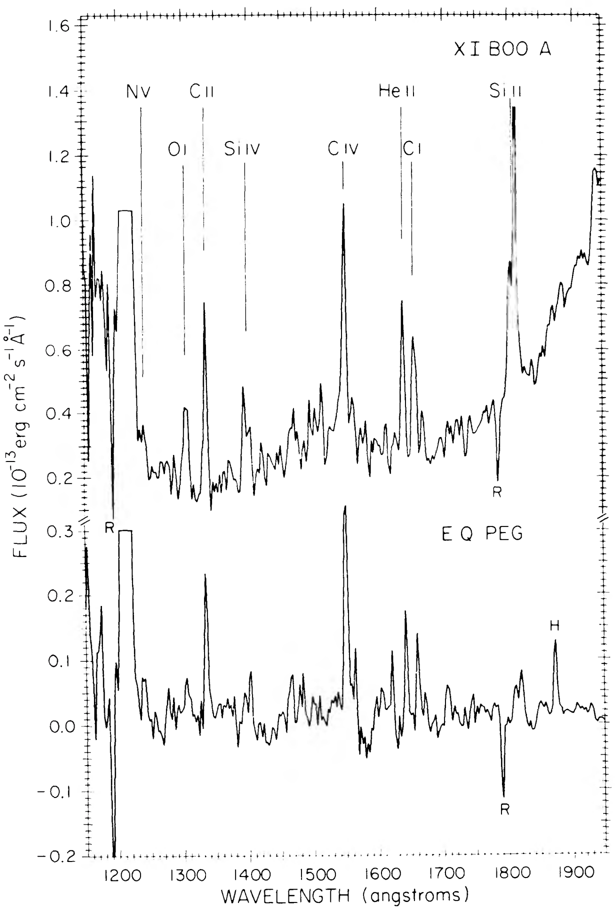

FIG. 1.—Short-wavelength spectra of EQ Peg and ξ Boo obtained with *IUE*. Prominent emission lines are marked. The symbol R denotes a fiducial mark (reseau). Geocoronal Lα is present at λ1216, and the profile has been truncated. H marks a radiation noise spike.

b) ξ *Bootis A*

The visual binary ξ Boo consists of a pair of main-sequence stars at present separated by 7".1. Both component A (G8 V, $V = 4.7$) and component B (K4 V, $V = 6.6$) have strong, variable Ca II emission (Wilson 1978). Two *IUE* exposures of this system, lasting 45 (SWP 1558) and 160 minutes (SWP 1559), were taken in the short-wavelength, low-dispersion mode.

The short-wavelength exposures were made by using the visual star tracker to center ξ Boo in the large aperture—a procedure which selects the brighter star. The large aperture is oval, with axes approximately 10" by 20", with the largest dimension roughly perpendicular to the dispersion; the stellar Lα emission was found to be centered within the extended geocoronal Lα emission. At the time of observation, the projected separation of the two stars along the long slit direction was about 4"; if both stars contributed a comparable amount of emission, the spectrum would have appeared to be spatially broadened (FWHM of a point source is $\sim$5".4). Since the spectrum is not broadened, we conclude that star A produced virtually all of the observed flux.

In Figure 1, the ultraviolet spectrum of ξ Boo A (from the longer of the two exposures) is compared to that of EQ Peg. It is apparent that the same lines are present in the two spectra, with ξ Boo A, the hotter star, showing continuum flux as well.

III. DISCUSSION

Line identifications and fluxes for EQ Peg and ξ Boo are listed in Table 1. For ξ Boo the fluxes of the stronger lines were averaged between the two exposures, while the fluxes of the weaker lines were taken from the longer exposure. The two exposures were separated by 4 hours; the measured fluxes of strong lines agree to about 20%, and the weak lines to about 30%. This appears to be the level of repeatability for spectra of different exposure times and background levels. The scale for fluxes received at the Earth is based on the *IUE* flux calibration (Bohlin *et al.* 1979).

The ions observed are typical of the solar transition region. In order to make meaningful comparisons, we converted the observed fluxes to stellar surface fluxes using the Barnes-Evans (1976) relation between angular diameter, apparent magnitude, and $V - R$. The photometry for ξ Boo A was taken from Johnson *et al.* (1966); for EQ Peg we used the values given by Veeder (1974) for the primary alone. The resulting angular diameters are 1.31 ms for ξ Boo A and 0.71 ms for the EQ Peg primary. If one star dominates, the surface fluxes listed in Table 1 are appropriate; if both components are comparable, the surface fluxes for each star are reduced by a factor of 2.

In Table 2 the surface fluxes have been divided by the corresponding values for the quiet Sun. For comparison, the same ratios are listed for ϵ Eri, a fairly active K2 dwarf with smaller surface fluxes than ξ Boo or EQ Peg (Linsky *et al.* 1978), and for solar active regions. The transition-region line fluxes for ξ Boo and EQ Peg are remarkably similar. They have enhanced fluxes in all lines relative to the average Sun, but are most enhanced in the high-temperature lines, and He II λ1640. The enhancements are very similar to the enhancement of solar active regions over the quiet Sun, as given in Table 2. The K2 dwarf ϵ Eri appears to represent an intermediate situation, both in terms of surface fluxes and line ratios.

The strength of the He II λ1640 line deserves special comment. In the quiet Sun λ1640 is formed by collisional excitation (~70%) and by recombination following photoionization by coronal XUV radiation (~30%; Kohl 1977). According to the analysis of Raymond, Noyes, and Stopa (1979) and the theoretical X-ray

TABLE 1

LINE IDENTIFICATIONS AND FLUXES

EQ PEGASI				ξ BOOTIS A (HD 131156)			
λ_{obs}	$f_{\oplus}$[a] ($\times 10^{-13}$)	Iden.	F[b] ($\times 10^4$)	λ_{obs}	$f_{\oplus}$ ($\times 10^{-13}$)	Iden.	F[b] ($\times 10^4$)
1215..........	sat	Lα	...	1215........	$\gtrsim$10	Lα	$\gtrsim$10
1236.2........	(0.53)	N V	(1.7)	1240.0......	(0.5)	N V	(0.5)
1305.4........	0.55	O I	1.8	1301.2......	3.2	O I	3.2
1335.0........	1.5	C II	5.0	1335.4......	4.7	C II	4.7
1393.4........	0.28	Si IV	0.90	1391.0......	1.5	Si IV	1.5
1404.0........	0.38	Si IV	1.30	1401.6......	1.0	Si IV	1.0
1468.2?.......	(0.43)	...	(1.4)	...	...	...	...
1551.2........	2.6	C IV	8.4	1547.0......	8.5	C IV	8.4
				1557.6?.....	1.0	C I?	1.0
1641.0........	0.64	He II	2.1	1636.6......	3.7	He II	3.7
1659.0........	0.57	C I	1.8	1655.4......	2.5	C I	2.5
1812.0........	0.28	Si II	0.90	1804.0......	2.6	Si II	2.6
1820.0........	0.40	Si II	1.3	1814.6......	6.5	Si II	6.5

NOTE.—Values in parentheses are very uncertain; sat = saturated; estimated accuracy ~20% for fluxes $>10^{-13}$ ergs cm^{-2} s^{-1}, 30% for weaker fluxes.

[a] Flux received at Earth in ergs cm^{-2} s^{-1}.

[b] Flux at stellar surface in ergs cm^{-2} s^{-1} assuming one star only (see text). (This equals $2\pi \int I \mu d\mu$).

TABLE 2

SURFACE FLUXES RELATIVE TO QUIET SUN

Ion	T_{max}(K)	EQ Pegasi (dM5e)	ξ Bootis (G8 V)	ϵ Eridani[a] (K2 V)	AR/QS[b]	VAR/QS[b]
N V...........	2×10^5	(21)	(6.0)	5.3	9.0	12.6
C IV..........	1.3×10^5	14.5	14.5	2.9	4.4[c]	4.0?[c]
Si IV..........	8.3×10^4	8.8	10.1	4.3	4.1[c]	5.9[c]
He II.........	2×10^4	16.2	28.5	12.3	15.6[c]	22.3[c]
C II...........	2×10^4	10.8	10.2	3.3	4.5[c]	7.0[c]
O I............	(9000)[d]	4.3	8.0	3.8	3.9	5.4
C I............	7000	3.4	4.7	2.3	2.0[c]	2.8[c]
Si II..........	6300	1.4	5.7	2.6	2.1[c]	3.1[c]

[a] From Linsky *et al.* 1978.

[b] Ratios of active region to quiet Sun, and very active region to quiet Sun, taken from Vernazza and Reeves 1978. Quiet Sun values from Rottman, quoted by Linsky *et al.* 1978.

[c] Taken from wavelength lines shorter than in Table 1.

[d] May be pumped by Lβ, hence uncertain T_{max}.

emission spectra of Raymond and Smith (1977), recombination accounts for $\sim 60\%$ of the $\lambda 1640$ emission in solar active regions. Using these results, we derive the relationship $F_x = CF_{\lambda 1640}$ between the 0.25 keV band (40–60 Å) coronal X-ray flux F_x and the resulting $\lambda 1640$ flux. Our calculations show $C \sim 50$ for coronal temperatures between 1×10^6 K and 2.5×10^6 K; C decreases very rapidly below 1×10^6 K. This implies an X-ray luminosity $L_x \sim 10^{28}$ ergs s^{-1} and emission measure $\mathrm{EM} = N_e^2 V \sim 10^{51}$ cm^{-3} for EQ Peg. The X-ray flux at Earth would be an order of magnitude lower than the flare observed on UV Ceti (Heise *et al.* 1975), but should be easily observable with *HEAO B*. Similarly for ξ Boo, the $\lambda 1640$ flux requires $L_x \sim 5 \times 10^{28}$ ergs s^{-1} and $\mathrm{EM} \sim 5 \times 10^{51}$ cm^{-3}. Walter, Charles, and Bowyer (1978) have observed the total X-ray luminosity of ξ Boo to be 2.4×10^{29} ergs s^{-1} in the 0.2–2.8 keV bandpass. If the coronal gas were isothermal at a temperature near 2×10^6 K, this luminosity would correspond to a 0.25 keV luminosity $\sim 6 \times 10^{28}$ ergs s^{-1}, in good agreement with the value derived from the $\lambda 1640$ flux. There would be a significant discrepancy if $T \lesssim 1.5 \times 10^6$ K or $T \gtrsim 3 \times 10^6$ K. The ratio of X-ray luminosity (44–60 Å) to optical luminosity is 10^{-4} for EQ Peg and 3×10^{-5} for ξ Boo; both values are considerably higher than an estimated solar value $\sim 10^{-7}$ (Manson 1977).

The sum of the fluxes of the lines of EQ Peg observed here amounts to a luminosity $L \sim 5 \times 10^{27}$ ergs s^{-1}, a value which is comparable to the time-averaged flare luminosity in the U bandpass (Lacy, Moffett, and Evans 1976). Thus the transition-region lines are important to any analysis of the chromospheric energy budget. Assuming a conduction-dominated homogeneous transition region, the average pressures for the high-temperature species are ~ 10 times quiet solar pressures.

IV. CONCLUSIONS

The chromospheres of the two active dwarfs discussed here are strikingly similar in their surface fluxes and line ratios, although their effective temperatures are different. The atmospheres are more like solar active regions than like the quiet Sun, exhibiting enhancements of high-temperature species, and particularly the He II $\lambda 1640$, which is indicative of still higher temperatures. If the chromospheric emission is nonuniform, as suggested by solar observations, the local surface fluxes (and hence pressures) could be considerably higher than those of solar active regions.

While we cannot rule out the possibility that our UV observations of EQ Peg refer to conditions resulting from a major flare, it seems most likely that the fluxes refer to an "average" time behavior. This is also suggested by the similarity of the surface fluxes of "nonflaring" active dwarfs, RS Canum Venaticorum stars, and W Ursae Majoris stars (Dupree *et al.* 1979; Linsky *et al.* 1978).

The similarity of the chromospheres of ξ Boo A and EQ Peg suggests that flares may occur on ξ Boo that are as energetic as those on EQ Peg, but that the higher photospheric surface brightness of ξ Boo prevents the observation of optical flares. The large amount of scatter in Wilson's (1978) Ca II observations of ξ Boo A also suggests chromospheric activity. It would be of some interest to monitor this star at X-ray and radio wavelengths to search for a direct relationship between flare activity and transition-region line fluxes.

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