A&A 488, 715–721 (2008)
DOI: 10.1051/0004-6361:20078501

Astronomy
&
Astrophysics

Active cool stars and He I 10 830 Å: the coronal connection★

J. Sanz-Forcada[1] and A. K. Dupree[2]

[1] Laboratorio de Astrofísica Espacial y Física Fundamental, INTA, PO Box 78, 28691 Villanueva de la Cañada, Madrid, Spain
e-mail: `jsanz@laeff.inta.es`
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA, USA
e-mail: `dupree@cfa.harvard.edu`

Received 17 August 2007 / Accepted 13 June 2008

ABSTRACT

Context. The mechanism of formation of the He I 10 830 Å triplet in cool stars has been subject of debate for the last 30 years. A relation between the X-ray luminosity and the He I 10 830 Å flux was found in cool stars, but the dominant mechanism of formation in these stars (photoionization by coronal radiation followed by recombination and cascade, or collisional excitation in the chromosphere), has not yet been established.
Aims. We use modern instrumentation (NOT/SOFIN) and a direct measurement of the EUV flux, which photoionizes He I, to investigate the formation mechanism of the line for the most active stars which are frequently excluded from analysis.
Methods. We have observed with an unprecedented resolution ($R \sim 170\,000$) the He I 10 830 Å triplet in a set of 15 stars that were also observed with the Extreme Ultraviolet Explorer (EUVE) in order to compare the line strengths with their EUV and X-ray fluxes.
Results. Active dwarf and subgiant stars do not exhibit a relation between the EUV flux and the equivalent width of the He I 10 830 Å line. Giant stars however, show a positive correlation between the strength of the He I 10 830 Å absorption and the EUV and X-ray fluxes. The strength of the C IV 1550 Å emission does not correlate with coronal fluxes in this sample of 15 stars.
Conclusions. Active dwarf stars may have high chromospheric densities thus allowing collisional excitation to dominate photoionization/recombination processes in forming the He I 10 830 Å line. Active giant stars possess lower gravities, and lower chromospheric densities than dwarfs, allowing for photoexcitation processes to become important. Moreover, their extended chromospheres allow for scattering of infrared continuum radiation, producing strong absorption in He I and tracing wind dynamics.

Key words. stars: activity – stars: late-type – line: formation – stars: chromospheres – infrared: stars – X-rays: stars

1. Introduction

Observations of the solar corona and chromosphere reveal that regions with copious X-ray emission (emitted by bright points or active regions in the corona) also have enhanced He I 10 830 Å absorption that arises in the chromosphere (Fig. 1). Conversely, chromospheric regions located below solar coronal holes, where X-rays are diminished, show weakened He I absorption (Zirin 1975; Sheeley & Harvey 1981; Dupree et al. 1996). The He I 10 830 Å line, actually a triplet (10 829.081 Å, 10 830.250 Å, and 10 830.341 Å), is a transition between the lower, metastable level (2^3S) in the triplet series of He I and the 2^3P level (Fig. 2). The metastable 2^3S level can be populated only through collisional excitation from the ground level or through recombination and deexcitation from upper levels. Two mechanisms have been proposed for the population of the lower 2^3S level. In the photoionization-recombination (PR) mechanism (Goldberg 1939), X-rays and EUV radiation ($\lambda < 504$ Å) from the corona photoionize the neutral helium from the ground state; photoionization is followed by recombination, and the electrons cascade to populate the lower levels of He I, especially the metastable 2^3S level. Scattering of the local infrared continuum produces an absorption line. Models suggest (Andretta & Jones 1997) the PR process is important in the Sun at temperatures <10 000 K. However, the opacity of the chromosphere can limit the efficiency of the photoionization mechanism. In an alternative mechanism, electron collisions from the ground and the metastable 2^3S level of He I dominate photoionization. In this case, a temperature ~20 000–30 000 K is required, and high densities in the chromosphere and transition region enhance the process. A combination of the two processes can exist as well. Arguments for each of the mechanisms can be found in Zirin (1982); Simon et al. (1982); Smith (1983);

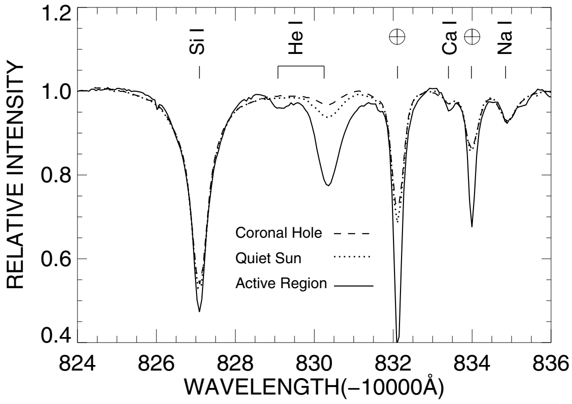

Fig. 1. Spectra of different solar regions: coronal hole, quiet Sun, and an active region (from Dupree et al. 1996, with spectra from an active region courtesy of Penn).

★ Figures 5 and 6 are only available at `http://www.aanda.org`

Article published by EDP Sciences

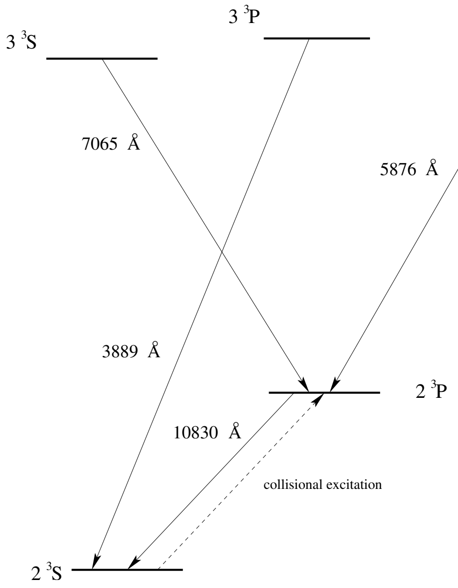

Fig. 2. Energy level diagram of the triplet series in He I showing the 10 830 Å transition. The broken arrow indicates collisional excitation is possible in regions with high density.

Wolff & Heasley (1984); O'Brien & Lambert (1986); Zarro & Zirin (1986); Lanzafame & Byrne (1995); Andretta & Giampapa (1995); Andretta & Jones (1997); Pietarila & Judge (2004), and references therein.

If the PR mechanism dominates the formation of the 10 830 Å transition, a correlation is expected between the strength of the helium line and the radiation field at $\lambda < 504$ Å located in the EUV and X-ray bands. Several studies have compared the equivalent widths (*EW*) of the He I 10 830 Å line and the X-ray flux in late-type stars in order to establish a relation between those parameters. Theses studies show that stronger X-ray emission yields stronger 10 830 Å absorption in both dwarfs (of spectral type F7 or later) and giants (Zirin 1982; O'Brien & Lambert 1986; Zarro & Zirin 1986). However the RS CVn active binary systems were generally not included in these analyses. Many of the previous observations made use of photographic plates to measure the 10 830 Å line, and correlated the line strengths with the X-ray fluxes observed by the Einstein satellite (IPC and HRI instruments) which spanned the energy range 0.1–4 keV. In this paper we present measurements of the 10 830 Å line in very active cool stars and binaries taken with modern instrumentation and high resolution. The use of high spectral resolution is essential in order to discern blends with telluric lines. Additionally, EUV fluxes are obtained as measured directly with the Extreme Ultraviolet Explorer (EUVE). Since the photoionization edge of He I is located at 504 Å (0.02 keV), the EUV fluxes are expected to relate closely to the photoionization rate of helium.

The chromospheric line of He I at 10 830 Å can indicate bulk mass motions in the atmospheres of cool luminous stars. The lower level of the transition is metastable, and a large population can build up in this level. If the gas itself is moving outward in a wind, the helium in the metastable level in the outflow scatters photospheric infrared radiation, and the line profile can reveal the dynamics of the atmosphere. If there is a significant contribution by the photoionization-recombination process, then the level population is independent of the local thermodynamic conditions in the chromosphere. In all cases, detailed modeling demonstrates (see Dupree et al. 1992) that in luminous stars, the Helium atom is formed further out in the atmosphere than other optical diagnostics of mass flow such as Hα and Ca II H & K lines, making it an extremely sensitive probe of the acceleration region of a stellar wind. Even in a dwarf star, such as the Sun, models demonstrate that the 10 830 Å line is formed above the Ca II K core and Hα (Avrett 1998) so that this Helium transition is more favorable for detecting regions where acceleration is likely to occur. Most importantly, observations of the 10 830 Å line in both Sun and stars demonstrate that high outflow velocities are observed in the line profiles of cool stars (see e.g. O'Brien & Lambert 1986; Dupree et al. 1992, 1996; Edwards et al. 2003; Dupree et al. 2005a). Given the high spectral resolution of our observations, the presence of winds in the stars of the sample can be explored. The cool giants are especially good targets.

In Sect. 2 we describe the observations. Section 3 compares the He I line strengths to other parameters. Results are discussed in Sect. 4; conclusions can be found in Sect. 5.

2. Observations

High-resolution infrared spectra of active binary systems and single stars (Table 1) were obtained during 11–19 August 2000 at the 2.56 m Nordic Optical Telescope (NOT) located at the Observatorio del Roque de Los Muchachos (La Palma, Spain). The Soviet Finnish High Resolution Echelle Spectrograph (SOFIN) was used to record spectra in the spectral range $\lambda\lambda \sim$ 10 800–10 870, with a resolution of $R \sim 170\,000$. This resolution allows the He I triplet (λ10 829.081, λ10 830.250, λ10 830.341) to be resolved and the profiles measured. It also provides clear separation from nearby lines, such as Si I 10 827.09 Å, Ti I 10 828.04 Å and the water vapor line at ~10 832.1 Å (Figs. 3–6). Exposure times varied from 120 s to 80 min; individual exposures were no longer than 20 min at most and depend on stellar magnitude. A ThAr lamp was used for the wavelength calibration. We have reduced the data using standard procedures within the Image Reduction and Analysis Facility (IRAF) software package, developed by the US National Optical Astronomy Observatories (NOAO). Equivalent widths were measured from the normalized spectra by fitting multiple Gaussians to the blended profiles which at times included telluric lines. The contribution of telluric water vapor lines was subtracted from the Helium equivalent width. Since spectra were obtained at different orbital phases of the binaries, we have measured the equivalent widths displayed in Table 1 in the spectra with the widest velocity separation of the components. This ensures the least blending of individual features. Typical errors in the measurement of the equivalent width are less than 15%, and the line centers correspond to their theoretical values within 5 km s^{-1}. We tested the line ratio between λ10 830.250 + λ10 830.341 and λ10 829.081 in ϵ Eri. A line ratio of 6.5 ± 3.6 is measured, consistent with the expected value of 8 based on *gf* values. ξ UMa B has a ratio of 9.6 ± 0.5, which is also reasonable.

Spectroscopic observations taken with the Extreme Ultraviolet Explorer (EUVE) satellite were obtained from the MAST Archive at Space Telescope Science Institute (STScI), and also directly from the EUVE project for our Guest Investigator targets. Fluxes in the 80–170 Å range were calculated from the EUVE spectra by first summing all available spectra. The summed fluxes were corrected for absorption by the interstellar medium as explained in Sanz-Forcada et al. (2003). Although it would be possible with EUVE to measure

Table 1. Data for target stars (targets selected from Sanz-Forcada et al. 2003).

Star	HD	Spectral type	d [pc]	He I 10 830 W_λ [Å]	Date, UT [midpoint]	log $L_{\rm EUV}$ [erg s^{-1}]	$F_{\rm EUV}$[1] [erg cm^{-2} s^{-1}]	$F_{\rm He\,II\ 304}$ [erg cm^{-2} s^{-1}]	log $L_{\rm X}/L_{\rm bol}$	$F_{\rm C\,IV}$ [erg cm^{-2} s^{-1}]
β Cet	4128	K0III	29.4	0.890	16/08/2000, 03:48	29.6	3.56 E–12	6.06 E–13	–5.3	9.64 E–13
AY Cet	7672	WD/G5III	78.5	0.880	15/08/2000, 04:05	30.3	2.67 E–12	(8.61 E–13)[2]	–4.1	9.06 E–13
VY Ari	17 433	K3-4V-IV + ?	44.0	0.400	14/08/2000, 04:08	30.2	7.16 E–12	9.65 E–13	–3.2	4.70 E–13
UX Ari	21 242	G5V/K0IV	50.2	0.240	16/08/2000, 04:40	30.5	10.7 E–12	17.9 E–13	–3.3	11.5 E–13
ϵ Eri	22 049	K2V	3.22	0.310	13/08/2000, 05:46	27.5	2.57 E–12	21.4 E–13	–4.8	11.7 E–13
V711 Tau	22 468	G5IV/K1IV	29.0	0.090	17/08/2000, 05:47	30.1	12.0 E–12	46.1 E–13	–3.0	35.6 E–13
Capella	34 029	G1III/G8III	12.9	0.630	15/08/2000, 06:47	29.4	11.5 E–12	125 E–13	–5.3	416 E–13
σ Gem	62 044	K1III + ?	37.5	1.110	14/04/2000, 20:19	30.2	9.33 E–12	20.4 E–13	–4.1	30.7 E–13
ξ UMa B	98 230	G5V/[KV]	8.35	0.380	17/04/2000, 21:45	28.5	4.11 E–12	18.5 E–13	–4.3	10.4 E–13
BH CVn	118 216	F2IV/K2IV	44.5	0.190	13/08/2000, 20:20	29.7	2.34 E–12	33.9 E–13	–4.2	14.5 E–13
σ^2 CrB	146 361	F6V/G0V	21.7	0.320	18/08/2000, 22:23	29.8	12.0 E–12	63.8 E–13	–3.4	26.1 E–13
AR Lac	210 334	G2IV/K0IV	42.0	0.760	14/08/2000, 02:20	30.0	5.21 E–12	14.5 E–13	–3.4	14.9 E–13
λ And	222 107	G8IV-III + ?	25.8	1.010	15/08/2000, 03:10	29.9	10.3 E–12	24.5 E–13	–4.3	30.4 E–13
II Peg	224 085	K2IV/M0-3V	42.3	0.300	12/08/2000, 03:45	30.0	5.12 E–12	11.4 E–13	–2.8	4.82 E–13

[1] Flux at Earth, corrected for interstellar absorption. EUV flux in range 80–170 Å, X-ray flux in range 0.1–2.4 keV; [2] calculated from the $L_{\rm EUV}$ vs. $L_{\rm He\,II\ 304}$ relation in the rest of sample.

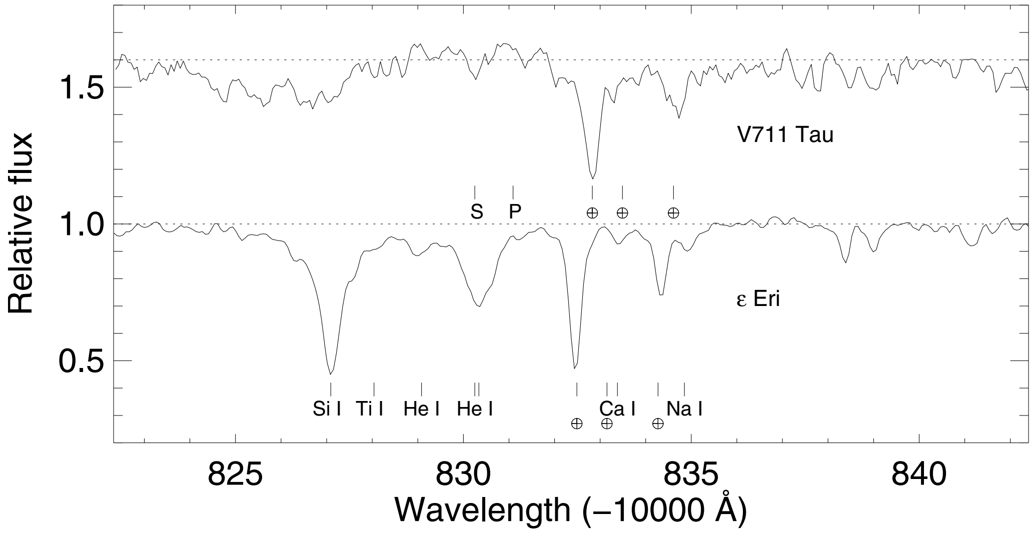

Fig. 3. Spectra of ϵ Eri and V711 Tau. Positions of the He I 10 830.25 Å line corresponding to the primary (P) and secondary (S) components of V711 Tau are marked. In this observation of V711 Tau (16/08/2000, 6:07 UT) the He I 10 830 line is slightly in emission, which can arise in an extended atmosphere.

the flux close to the helium edge at 504 Å, in most cases the spectra were absorbed by the interstellar medium at those wavelengths and could not give reliable measurements. (The flux in the range 170–370 Å can be as much as 14 times the flux in photon units in the 80–170 Å range). The measurement of the He II 304 Å line is also possible in most cases, but the extraction is difficult because the large aperture is filled with airglow around this line. We treat it in similar fashion as sky subtraction in a slit used for optical spectroscopy. In the case of AY Cet, where no measurement of the 304 Å line was available, we used the relation observed between values of $L_{\rm EUV}$ and $L_{\rm HeII\ 304}$ in the sample to calculate the expected value of $L_{\rm HeII\ 304}$ (Table 1). Finally, X-ray fluxes (0.1–2.4 keV) obtained with the Roentgen Satellite (ROSAT) were taken from the Rosat All Sky Survey (RASS) data (Voges et al. 1999, and references therein).

Many of these targets exhibit flux variations in the EUV spectral range. Flaring can cause short-lived increases that may amount to a factor of 6; some targets also show changes when active regions presumably rotate into view (Sanz-Forcada et al. 2002; Osten & Brown 1999). Long pointings with the EUVE satellite towards σ Gem, V711 Tau, UX Ari (Sanz-Forcada et al. 2002) and β Cet (Ayres et al. 2001) reveal that the EUVE fluxes of these targets are modulated by a factor of 1.2 (β Cet), 2 (σ Gem), 3 (V711 Tau), and 5 (UX Ari), outside of flaring episodes (see also Fig. 7).

3. Results

The secondary stars in binary systems are frequently more active than the primary due to the presence of a deeper convective region. In many cases, our spectra show a stronger 10 830 Å absorption line from the secondary star. Several stellar parameters are compared to investigate the dependence of the He I strength on the radiation field. Figure 8 shows the relation between the EUV luminosity at the star (corrected for interstellar absorption) and the equivalent width of the 10 830 Å absorption line. The active dwarf stars exhibit EUV luminosities that span a factor of about 1000, yet the He I equivalent width changes at most by a

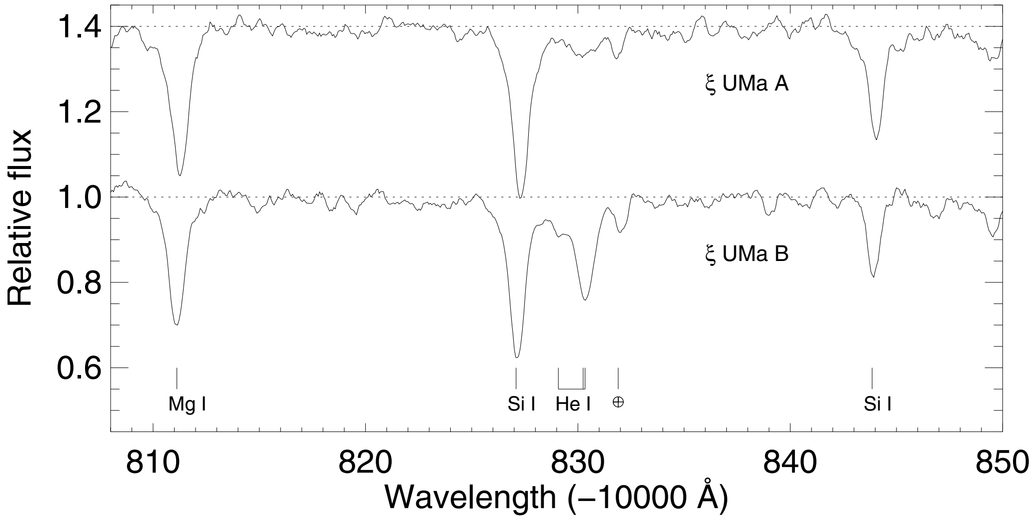

Fig. 4. Spectra of ξ UMa A and B. The He I 10 830 Å line reveals a substantial difference in activity between the A and B components (G0 + G5 dwarf stars respectively). The source of X-rays is the B member of this visual binary system which is itself a short-period (3.98 days) binary, observed pole-on. The B component exhibits the stronger He I absorption.

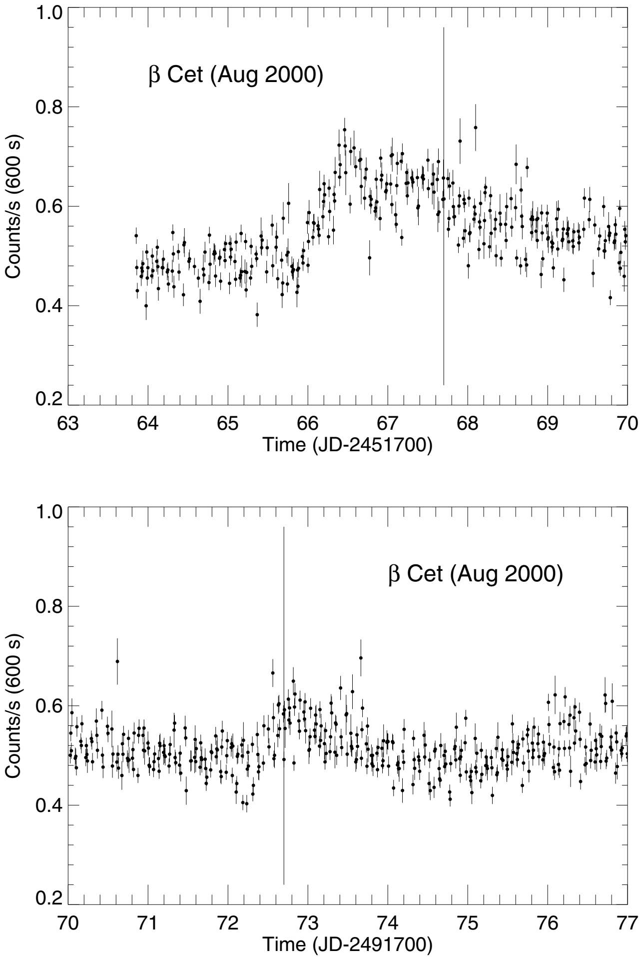

Fig. 7. EUVE light curve flux variation in β Cet over 14 days of continuous observation. Solid lines mark the times of the two He I 10 830 Å observations reported here. The first of these, with EW = 0.905 Å, corresponds to the first small EUV flare (see also Sanz-Forcada et al. 2003), and the second (EW = 0.873) is located precisely at the maximum of a small EUV flare.

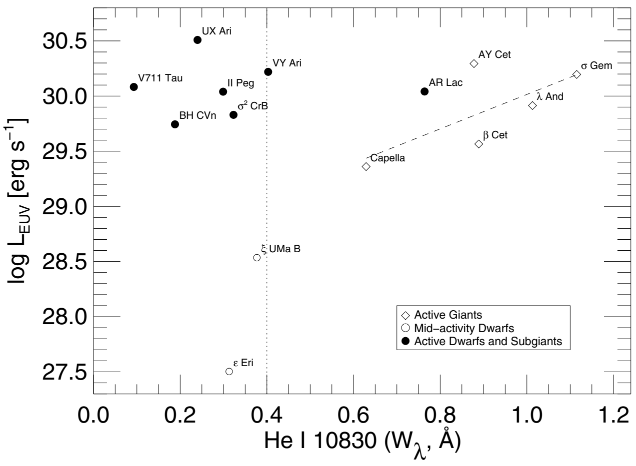

Fig. 8. EUV luminosity in the range 80–170 Å (EUV luminosities from Sanz-Forcada et al. 2003) vs. the equivalent width of the He I 10 830 Å triplet. Equivalent widths have typical errors of ≤0.1 Å. A dashed line indicates the linear fit to the giants (correlation factor r = 0.71). The dotted line at EW = 0.4 Å marks the limit suggested by models (Andretta & Giampapa 1995) of a single dwarf star and corresponds to our measured limit too. Note that AR Lac has two active stars and $EW \lesssim 0.8$ Å.

factor of 4. The dwarfs and subgiants have absorption equivalent widths not in excess of 400 mÅ. An exception is AR Lac, which has 2 active stars. The measured EW lies below 800 mÅ, and its value does not appear to be varying systematically with the EUV flux. Very active stars such as V711 Tau or UX Ari have a weak 10 830 Å line that possibly contains emission in one observation of V711 Tau (Fig. 3).

The He I λ10 830 line shows a different behavior in the 5 active giants (Figs. 8, 9). Here stronger He I absorption appears directly correlated with stronger EUVE or X-ray flux (correlation factor r = 0.71). The long-period binary Capella (α Aur) deserves special mention. Katsova & Shcherbakov (1998) monitored this system over 9 years and detected a variation of the

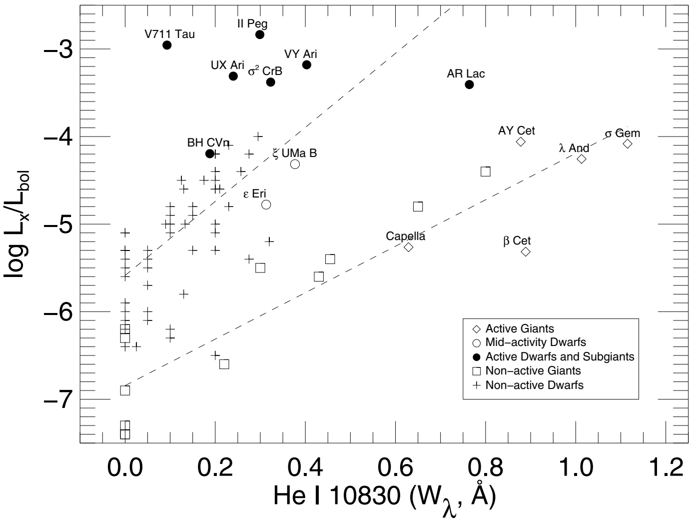

Fig. 9. $L_X/L_{\rm bol}$ vs. the equivalent width of the He I 10 830 Å triplet. Non-active stars are included from Zarro & Zirin (1986). Dashed lines indicate a linear fit to all giants (r = 0.92), and a linear fit to dwarfs and subgiants (r = 0.65).

equivalent width of the 10 830 Å line with orbital phase. At the time of our observations, the orbital phase was 0.79 which, in conjunction with the equivalent width, suggests that Capella was in a moderately active phase (see Fig. 4 of Katsova & Shcherbakov 1998). The total variation in equivalent width of λ 10 830 appears to be a factor of 1.5, and its value could be as high as 0.8 Å. Results from the EUVE satellite show that the EUV radiation from highly ionized Fe XX through Fe XXIII in Capella is modulated also on an orbital time scale (Dupree & Brickhouse 1995), by a factor ~2, although the effect on the total EUV flux is mitigated by the relatively constant flux of the strong Fe XVIII lines in the EUV region. Even when these variations are considered, Capella remains at the low end of the $W_\lambda - L_{\rm EUV}$ relation for giants shown in Fig. 8.

Broad wings in the giants λ And, β Cet, σ Gem, and Capella indicate mass motions or turbulence in the upper chromosphere of the star. Of particular note, the He absorption extends to shorter wavelengths to and, in some cases, beyond the Si I absorption line which lies 90 km s^{-1} distant. The He line absorption profile traces out the behavior of velocity in an expanding atmosphere. Since giant stars have extended chromospheres, these velocities become comparable to the stellar escape velocity, and can be said to mark the presence of a stellar wind. At the time when we observed the He I 10 830 Å line in λ And, Mirtorabi et al. (2003) monitored the star searching for periodicity in visible light and in photospheric spot coverage. During the period of our NOT observations of λ And, no important changes occurred in the observations of Mirtorabi et al. (2003), and the He I λ10 830 did not show substantial changes in strength either.

EUVE was also observing β Cet during our NOT campaign. Between the two NOT observations (JD 2 451 767.7 and 2 451 772.7) there were no changes in the line profiles or intensity. The NOT spectra are simultaneous with two local enhancements of similar strength in the EUVE light curve (Fig. 7 and Sanz-Forcada et al. 2003) that are likely due to a small flare or to an active region. However, our value of W_λ = 0.890 Å is larger than that (0.3 to 0.5 Å) measured by O'Brien & Lambert (1986) for β Cet, and the line depth also increased substantially in our observations. These may signal enhanced activity during the flaring episodes. The star β Cet, a presumably single giant (K0 III) follows the relation for giant stars that are members of RS CVn systems with respect to its EUV flux and λ10 830 equivalent width. Ions of high excitation, Fe XVIII through Fe XXIII have been observed directly in its EUV and far-UV spectrum (Sanz-Forcada et al. 2003; Redfield et al. 2003; Dupree et al. 2005b) and flaring episodes occur (Ayres et al. 2001). The star, β Cet, is a slow rotator, with $v \sin i$ = 4 km s^{-1} (Fekel 1997), and it is puzzling how its activity appears comparable to the RS CVn objects. It is not out of the question that β Cet is observed pole-on, and in actuality may be an active binary system.

4. Discussion

In this sample of active stars, the dwarfs and subgiants show different behavior from that of the giants. In the dwarf stars, the increasing levels of activity (seen through the X-ray or EUV luminosities) do not cause more substantial He I 10 830 Å absorption. On the contrary, the absorption looks rather shallow (if not partly in emission) for very active stars such as V711 Tau. Modelling efforts carried out by Andretta & Giampapa (1995) conclude that there is a maximum limit in the equivalent width of this line of around ~400 mÅ in dwarf stars. For higher levels of activity the flux in the line is larger than in the continuum, and it becomes an emission line, resulting in a profile that is a balance of absorption and emission. The value of 400 mÅ corresponds to the maximum equivalent width found in our sample of dwarfs and subgiants corroborating the Andretta & Giampapa results. Zarro & Zirin (1986) concluded that for F, G, and K dwarfs (spectral type equal to F7 or later) with weak coronas ($L_X/L_{\rm bol} < 10^{-4}$), a relation exists between the X-ray flux and the equivalent width of the λ10 830 line. Our sample focuses on strong X-ray emitters, and for these objects the relation does not hold. It would appear that the densities in these active dwarfs become sufficiently high to allow collisional processes to become significant.

If we restrict the analysis to giants only, there is a clear relation: an increasing EUV or X-ray luminosity (Figs. 8, 9) corresponds to increasing equivalent widths of the He I 10 830 Å line. Such a relation was found earlier by Zirin (1982) and Smith (1983) using a large sample of giants observed with mostly photographic plates and X-ray fluxes from the Einstein satellite. Smith (1983) included several RS CVn stars in his tabulation, using EUV measurements from O'Brien (1980). Smith reported a relationship for giant stars, as did O'Brien & Lambert (1986). Our sample of active giants contains observations that are generally of better quality in both the 10 830 Å line and the X-ray flux. Moreover we measure the EUV flux directly, which is close to the helium edge (~504 Å); therefore it should be better related to the 10 830 Å flux if controlled by photoionization rather than radiation from shorter wavelengths. The flux of the He II 304 Å line could be added to the flux of the ionizing EUV radiation, but the relations do not change significantly since the 304 Å flux is generally much less than the total EUV flux. One of the stars (AY Cet) has no direct measurement of the 304 Å line. The quality of the spectra at longer wavelengths allows us to approximate the flux in the whole band 170–504 Å for only a few cases. For Capella, the most extreme case, the 304 Å line flux represents only ~20% of the total flux (in photon units) in the 80–504 Å band. Therefore we consider the He II 304 Å line to be only a minor contributor to the excitation of the 10 830 Å line in these stars.

We have also compared the EUV flux to that of the He II 304 Å line. If a PR mechanism dominates the 304 Å formation, we might find higher fluxes in the 304 Å line for higher EUV luminosities. However, collisional processes could produce a similar dependence. The strength of the He II 304 Å line is clearly related to the EUV flux, but it is also strongly correlated with the C IV flux. This is not surprising since collisions dominate the production of both the EUV and C IV emission. It is not possible with these spectra to evaluate the contribution of the PR mechanism to the formation of the 304 Å line. Since the He II 1640 Å line shares a level with the 304 Å line, we might use it to test the formation of the latter. However such an exercise was carried out for Capella (Dupree et al. 1993), and the 304 Å line had only ~30% of the expected flux for the measured 1640 Å line, perhaps resulting from interstellar medium absorption or opacity effects in the star itself.

The two competing mechanisms for formation of the 10 830 Å line could both be important in the stars of the sample. Since they have high temperatures in the transition regions, collisional population of the levels involved in the line formation can occur. Stars in the sample also have large X-ray and EUV fluxes causing photoionization of He I which is followed by recombination, populating the same levels. However the model proposed for dwarf stars by Andretta & Giampapa (1995), with collisional effects dominating for the active stars, predicts the maximum equivalent widths observed here. Their model is also consistent with the observed filled-in emission with increasing EUV flux.

The wings of the He I 10 830 Å line in giants are broader than in dwarf stars which is indicative of mass motions and outflows that are likely present in the upper chromosphere or at the base of coronal loops. Katsova & Shcherbakov (1998) proposed that the formation of EUV lines and the He I 10 830 Å line in stars such as Capella results from a magnetized stellar wind forming a shock in the corona of the companion star. Now we know that the EUV fluxes found in Capella are similar to those found in other single active stars (Sanz-Forcada et al. 2003), and therefore strong EUV emission is not linked to binarity. The most logical explanation is that EUV lines are formed in dense coronal loops hotter than those found in the Sun, and the 10 830 Å line is formed as a consequence of the EUV flux, and additionally through collisional effects in the hot environment of the transition region.

An uncertainty remains whether the He I absorption for the giants is controlled by the EUV/X-ray flux, or whether it simply reflects a general increase in magnetic activity represented by dense regions and subsequent radiative losses from the star. O'Brien & Lambert (1986) suggested that the Helium I line strength in giants and supergiants correlated as well with other lines known to be collisionally excited, and hence is, in fact, independent of the EUV/X-ray flux. Our small sample shows no such correlation (Fig. 10). For the dwarf stars, the luminosity of the collisionally excited C IV multiplet (λ1550) shows a saturation in C IV and a limiting value (400 mÅ) of the He I equivalent width (Figs. 8 and 10). The giant stars show no correlation ($r = -0.31$) between C IV and the He I equivalent width (Fig. 10), suggesting that collisions are not significant in increasing the strength of He I. The radiation field must therefore influence the line strength of He I. While the X-ray and EUV fluxes themselves are correlated (Fig. 11), the EUV and C IV fluxes are not correlated for the active dwarfs and giants (Fig. 12). The small scale size of the high temperature EUV-emitting regions (Dupree et al. 1993; Sanz-Forcada et al. 2002, 2003) suggests they remain of comparable small size in stellar chromospheres of varying dimensions.

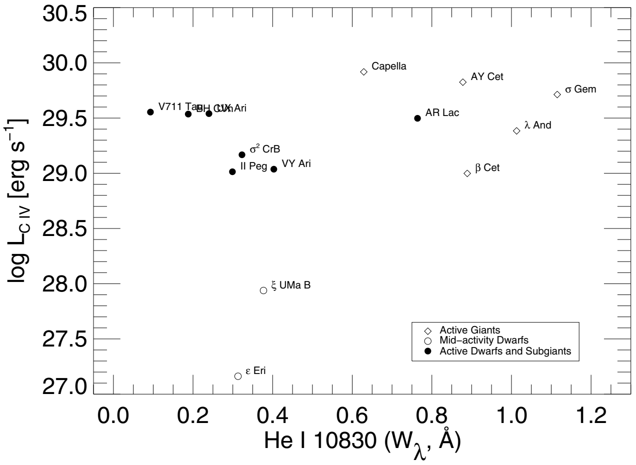

Fig. 10. C IV (λ1550) luminosity vs. He I λ10 830 equivalent width. Fluxes for C IV are taken from *IUE* spectra (see Sanz-Forcada et al. 2002, 2003).

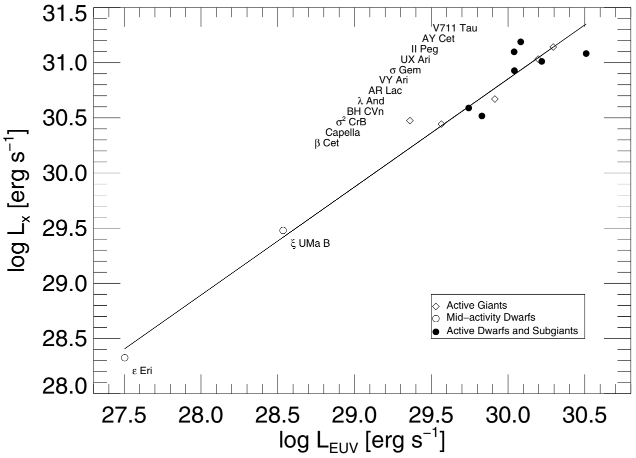

Fig. 11. X-ray vs. EUV luminosity for the stars in this sample. Not surprisingly, a correlation is present ($r = 0.98$), since both spectral regions are dominated by collisionally excited line emission formed at similar high temperatures.

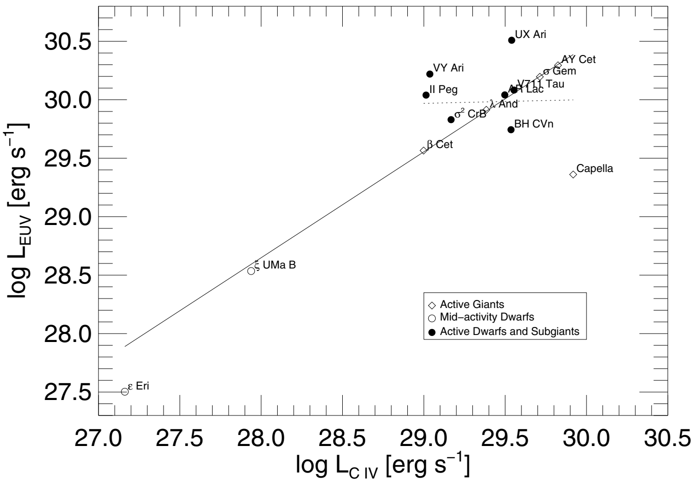

Fig. 12. EUV luminosity vs. C IV (λ1550) luminosity. A fit to all the stars is shown in solid line ($r = 0.86$), while the dashed line excludes ϵ Eri and ξ UMa B from the fit ($r = 0.03$).

5. Conclusions

The He I λ10 830 line responds differently to the EUV radiation field between the dwarf and giant stars in our sample. Active dwarf stars reach a "saturated" equivalent width in λ10 830 in the presence of a strong radiation field. This behavior appears consistent with model calculations in which high chromospheric densities allow collisional excitation to dominate photoionization/recombination processes in forming the line. Giant stars, with lower chromospheric densities than dwarfs, show increased He I absorption related to an increased EUV radiation field and the absorption is strengthened by an extended expanding atmosphere scattering the line. The He I line in giant stars has a photoionization-recombination component that appears to dominate the line-forming process. Detailed radiative transfer calculations would be helpful to assess the contribution of collisions to line formation in the giant stars.

Acknowledgements. We are grateful to Ilya Ilyin for assistance with the observing activities at the NOT. In addition, we thank the Spanish TAC for the allocation of telescope time at the NOT. We acknowledge the anonymous referee, who helped greatly in clarifying the analysis and presentation of the results. This work made use of the Smithsonian/NASA Astrophysics Data System and SIMBAD, a product of the Centre de Données astronomique de Strasbourg.

References

Andretta, V., & Giampapa, M. S. 1995, ApJ, 439, 405
Andretta, V., & Jones, H. P. 1997, ApJ, 439, 375
Avrett, E. H. 1998, in Solar Electromagnetic Radiation Study for Solar Cycle 22, ed. J. M. Pap, C. Frohlich, & R. K. Ulrich, 449
Ayres, T. R., Osten, R. A., & Brown, A. 2001, ApJ, 562, L83
Dupree, A. K., & Brickhouse, N. S. 1995, in Stellar Surface Structure Poster Proceedings, IAU Symp., 176, 184
Dupree, A. K., Sasselov, D. D., & Lester, J. B. 1992, ApJ, 387, L85
Dupree, A. K., Brickhouse, N. S., Doschek, G. A., Green, J. C., & Raymond, J. C. 1993, ApJ, 418, L41
Dupree, A. K., Penn, M. J., & Jones, H. P. 1996, ApJ, 467, L121
Dupree, A. K., Brickhouse, N. S., Smith, G. H., & Strader, J. 2005a, ApJ, 625, L131
Dupree, A. K., Lobel, A., Young, P. R., et al. 2005b, ApJ, 622, 629
Edwards, S., Fischer, W., Kwan, J., Hillenbrand, L., & Dupree, A. K. 2003, ApJ, 599, L41
Fekel, F. C. 1997, PASP, 109, 514
Goldberg, L. 1939, ApJ, 89, 673
Katsova, M. M., & Shcherbakov, A. G. 1998, A&A, 329, 1080
Lanzafame, A. C., & Byrne, P. B. 1995, A&A, 303, 155
Mirtorabi, M. T., Wasatonic, R., & Guinan, E. F. 2003, AJ, 125, 3265
O'Brien, Jr., G. T. 1980, Ph.D. Thesis (U. Texas: Austin)
O'Brien, Jr., G. T., & Lambert, D. L. 1986, ApJS, 62, 899
Osten, R. A., & Brown, A. 1999, ApJ, 515, 746
Pietarila, A., & Judge, P. G. 2004, ApJ, 606, 1239
Redfield, S., Ayres, T. R., Linsky, J. L., et al. 2003, ApJ, 585, 993
Sanz-Forcada, J., Brickhouse, N. S., & Dupree, A. K. 2002, ApJ, 570, 799
Sanz-Forcada, J., Brickhouse, N. S., & Dupree, A. K. 2003, ApJS, 145, 147
Sheeley, N. R. J., & Harvey, J. W. 1981, Sol. Phys., 70, 237
Simon, T., Linsky, J. L., & Stencel, R. E. 1982, ApJ, 257, 225
Smith, M. A. 1983, AJ, 88, 1031
Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389
Wolff, S. C., & Heasley, J. N. 1984, PASP, 96, 231
Zarro, D. M., & Zirin, H. 1986, ApJ, 304, 365
Zirin, H. 1975, ApJ, 199, L63
Zirin, H. 1982, ApJ, 260, 655

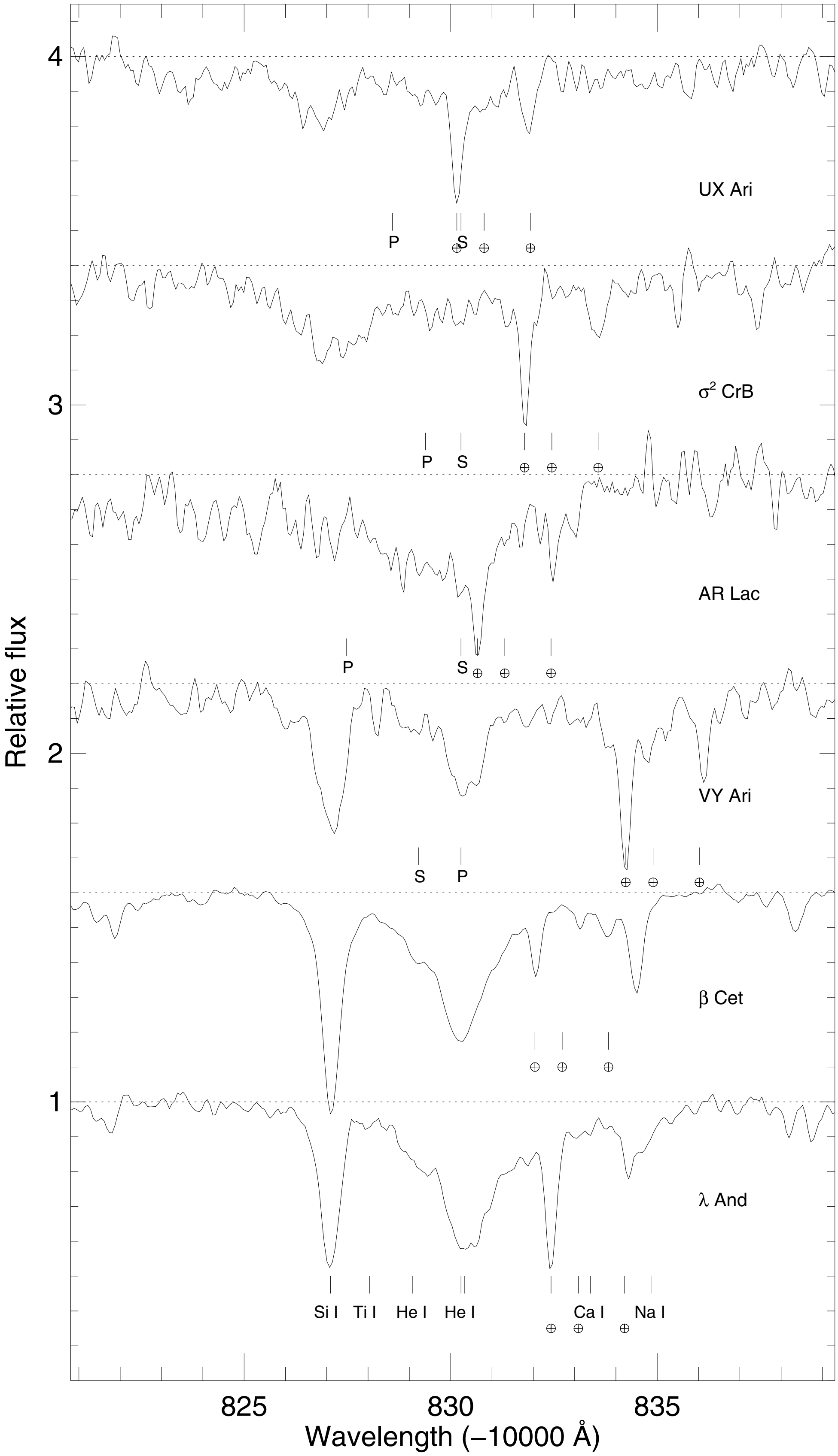

Fig. 5. Spectra of several sources normalized to 1 (indicated by the broken lines) and offset in this plot. Positions of the strongest line in the He I multiplet, λ10 830.25 corresponding to the primary (P) and secondary (S) components of binaries are marked. The profile of Si I reveals broadening due to turbulence in the stellar photosphere and rotation.

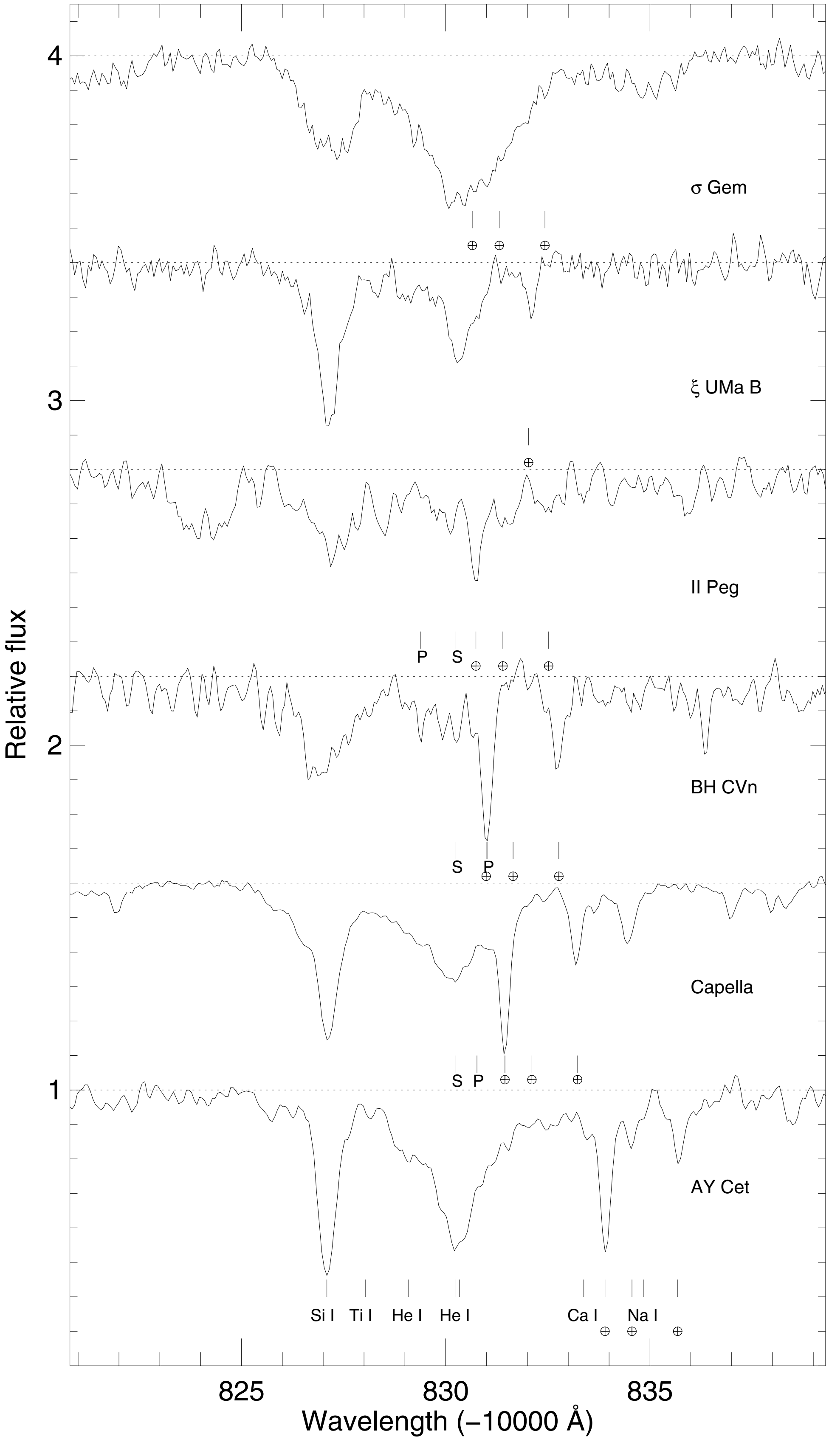

Fig. 6. Same as Fig. 5.