Active cool stars and He I 10830 Å: the coronal connection

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ABSTRACT

Context. The mechanism of formation of the He I 10830 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 10830 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 10830 Å triplet in a set of 15 stars that were also observed with the Extreme Ultraviolet Explorer (EUV) 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 10830 Å line. Giant stars however, show a positive correlation between the strength of the He I 10830 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 10830 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 10830 Å absorption that arises in the chromosphere (Fig. 1). Conversely, chromospheric regions located below solar coronal holes, where active regions in the corona) also have enhanced He I regions with copious X-ray emission (emitted by bright points or

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range 0.1 – 4 keV. In this paper we present measurements of the 10830 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 10830 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 10830 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 10830 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. Sect. 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 λλ 10800–10870, with a resolution of R ≈ 170,000. This resolution allows the He I triplet (λ10829.081, λ10830.250, λ10830.341) to be resolved and the profiles measured. It also provides clear separation from nearby lines, such as Si i 10827.09 Å, Ti i 10828.04 Å and the water vapor line at λ10832.1 Å (Fig. 3). 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 U.S. 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 λ10830.250 + λ10830.341 and λ10829.081 in ξ UMa. 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 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 $L_{\text{EUV}}$ and $L_{\text{HeII 304}}$ in the sample to calculate the expected value of $L_{\text{HeII 304}}$ (Table I). 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 β 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 10830 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. Fig. 8 shows the relation between the EUV luminosity at the star (corrected for interstellar absorption) and the equivalent width of the 10830 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 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 10830 Å line that possibly contains emission in one observation of V711 Tau (Fig. 3).

The He I 10830 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 ($\alpha$ Aur) deserves special mention. Katsova & Shcherbakov (1998) monitored this system over 9 years and detected a variation of the equivalent width of the 10830 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 $\lambda$ 10830 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 XXVI 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 xxm lines in the EUV region. Even when these variations are considered, Capella remains at the low end of the $W_\lambda-L_{\text{EUV}}$ relation for giants shown in Fig. 8.

Broad wings in the giants $\lambda$ 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 ab-

Fig. 3. Spectra of ε Eri and V711 Tau. Positions of the He I 10830.25 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 U.T.) the He I 10830 line is slightly in emission, which can arise in an extended atmosphere.
There were no changes in the line profiles or intensity during the campaign. Between the two NOT observations (JD 2451767.7 and 2451772.7) 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 $W_t = 0.890$ 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 $\lambda$10830 equivalent width. Ions of high excitation, Fe xxi through Fe xxv 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.)

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

| Star          | HD (number) | Spectral Type | d (pc) | $W_t$ (Å) | Date, U.T. log | $\log L_{EUV}$ | $F_{EUV}$ | $F_{He\ I \ 304}$ | $\log L_{X/L_{bol}}$ | $F_{C IV}$ |
|---------------|-------------|---------------|--------|-----------|----------------|----------------|-----------|------------------|---------------------|-----------|
| 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)     | -4.1                | 9.06 E-13  |
| VY Ari        | 17433       | 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        | 21242       | 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  |
| η Eri         | 20249       | 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      | 22468       | 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       | 34029       | 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         | 62044       | 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 A       | 98230       | 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        | 118216      | 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  |
| σ² CrB        | 146361      | 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        | 210334      | 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         | 222107      | 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  |
| η Peg         | 224085      | 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 $L_{EUV}$ vs. $L_{He\ I \ 304}$ relation in the rest of sample
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, $\lambda 10830.25$ 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.
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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 10830 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.

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 10830 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≤0.8 Å.

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 10830 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 10830 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 10830 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 10830 Å line in these stars.
We have also compared the EUV flux to that of the He\textsc{i} 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\textsc{i} 304 Å line is clearly related to the EUV flux, but it is also strongly correlated with the C\textsc{iv} flux. This is not surprising since collisions dominate the production of both the EUV and C\textsc{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\textsc{i} 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 \sim 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 10830 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\textsc{i} which is followed by recombinations, 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\textsc{i} 10830 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\textsc{i} 10830 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 10830 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\textsc{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\textsc{iv} multiplet (\lambda 1550) shows a saturation in C\textsc{iv} and a limiting value (400 mA) of the He\textsc{i} equivalent width (Fig. 8 and Fig. 10). The giant stars show no correlation (r = -0.31) between C\textsc{iv} and the He\textsc{i} equivalent width (Fig. 10), suggesting that collisions are not significant in increasing the strength of He\textsc{i}. The radiation field must therefore influenc
ence 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.

5. Conclusions

The He i λ10830 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 λ10830 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.

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