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# Dynamics of Coronal Iron Lines in Cool Stars based on FUSE and HST/STIS Observations

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**Abstract.**
We present UV observations of coronal forbidden lines of highly ionized iron. Fe XXI $\lambda$1354 and Fe XII $\lambda$1242 have been observed by spectrographs on board the Hubble Space Telescope (HST), and Fe XVIII $\lambda$975 recently has been identified in spectra taken by the Far Ultraviolet Spectroscopic Explorer (FUSE). Mass motions of hot gas in the corona provide information on the heating mechanism and magnetic field strength in the corona. Observations of forbidden iron lines with these moderate to high resolution spectrographs provide a unique opportunity to study high temperature dynamics of the hot coronal plasmas. We positively detect the forbidden iron line of Fe XVIII $\lambda$975 in five stars. $\beta$ Ceti shows the strongest Fe XVIII emission, and since it is a single star system, it is an ideal target to study stellar coronal dynamics. We find that the hot coronal plasma is confined, in contrast to observed downflows at the temperatures where the $10^5$ K lines like C III $\lambda$977 form.

## 1. Introduction

A multi-million degree stellar corona radiates primarily in the X-ray spectral region. However, forbidden transitions of highly ionized species also appear in the ultraviolet. Such forbidden lines have been observed in the quiescent solar corona and during strong flares (Feldman & Doschek 1991). The Fe XXI $\lambda$1354 forbidden line has been observed in the brightest coronal late-type stars, including AU Mic, HR 1099, and Capella (Maran et al. 1994; Robinson et al. 1996; Linsky et al. 1998). Unfortunately, the Fe XXI line is blended with a chromospheric C I emission line. The study of the dynamics of hot coronal plasma is complicated by two of these three sources being binary systems. Jordan et al. (2001) identified Fe XII $\lambda$1242 and Fe XII $\lambda$1349 in the spectrum of $\epsilon$ Eri, the first detection of these lines in a star other than the Sun. If the nearby N V $\lambda$1243 line is not too broad, Fe XII $\lambda$1242 can be used to study the dynamics of hot coronal plasma.

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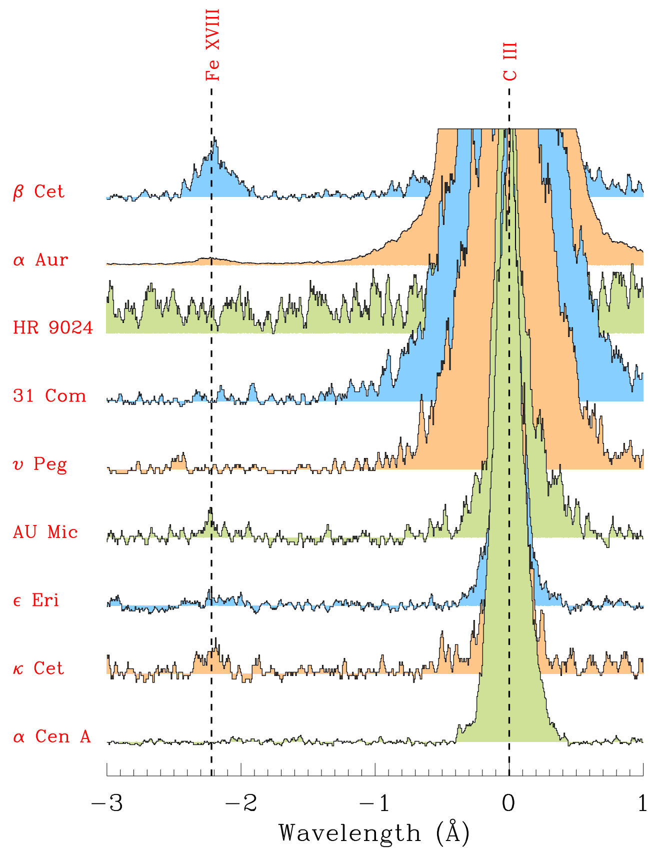


Figure 1. The spectral region around Fe XVIII for 9 stars. The strong transition region line, C III λ977 appears prominently in all targets. The Fe XVIII line is visible in many of the spectra. The wavelength scale is measured from the centroid of the C III line. The β Ceti spectrum exhibits the strongest Fe XVIII emission line. Stellar parameters and detections of other forbidden coronal iron lines are provided in Table 1.

## 2. Observations

The Far Ultraviolet Spectroscopic Explorer (FUSE) provides an excellent opportunity to observe another forbidden iron coronal line: Fe XVIII λ975. Fortunately, the line is uncontaminated by blends from other stellar emission lines. This line was initially identified in the coronally active binary Capella (Young et al. 2001). Since then, many other sources have been found with Fe XVIII emission. Figure 1 shows the spectral region around Fe XVIII for 9 stars. The strong transition region line, C III λ977 appears prominently in all the spectra, while the Fe XVIII line is visible in many of them. Table 1 summarises the stellar parameters, whether interstellar medium (ISM) absorption is apparent in C III λ977 (see Section 3), and if other coronal iron lines have been detected.

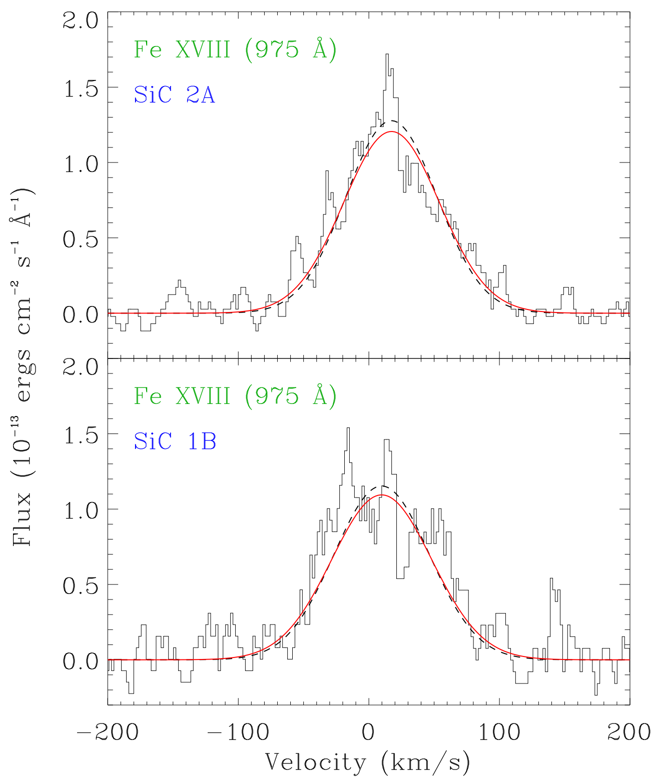


Figure 2. A single Gaussian fit is shown for the $\beta$ Cet Fe XVIII emission line. The red line shows the Gaussian stellar emission convolved with the FUSE instrumental line profile (Wood et al. 2001), and demonstrates that the line is fully resolved. The FUSE instrument provides redundant spectral coverage in two detector channels (SiC 2A and 1B) in the Fe XVIII spectral region. The fit parameters are provided in Table 2.

Table 1. Stellar Parameters and Coronal Iron detections

| HD # | other name | Spectral Type | Rad. Vel. (km/s) | C III 977 ISM abs. | Fe XVIII 975 flux | Fe XXI 1354 flux | Fe XII 1242 flux |
|---|---|---|---|---|---|---|---|
| 4128 | $\beta$ Cet | K0III | 13.0 | yes | yes | yes | no |
| 34029 | $\alpha$ Aur | G8III+G1III | 32.8,25.4 | yes | yes | yes | no |
| 223460 | HR 9024 | G1III | 0.7 | yes | no | yes | no |
| 111812 | 31 Com | G0III | –1.4 | no | no | yes | no |
| 220657 | $\upsilon$ Peg | F8IV | –11.1 | yes | ? | no | yes |
| 197481 | AU Mic | M0V | 1.2 | no | yes | yes | yes |
| 22049 | $\epsilon$ Eri | K2V | 15.5 | no | ? | no | yes |
| 20630 | $\kappa$ Cet | G5V | 19.9 | no | yes | yes | yes |
| 128620 | $\alpha$ Cen A | G2V | –24.6 | no | no | no | yes |

## 3. Analysis

The relative wavelength scale within a single detector channel on FUSE is accurate to $< 10$ km s$^{-1}$. However, lacking an on board calibration lamp, the FUSE absolute wavelength scale is only accurate to about 100 km s$^{-1}$. Fortunately, strong ISM absorption often is present in the neighboring C III $\lambda$977 line. ISM absorption appears in many spectral lines, and the velocity structure often is studied at very high spectral resolution (see The Colorado LISM Website: http://casa.colorado.edu/~sredfiel/ColoradoLIC.html). The velocity of ISM absorption remains fixed, despite changes in the stellar emission. C III ISM absorption is found in the strongest Fe XVIII source: $\beta$ Cet. The ISM absorption towards these two targets has been studied at high resolution (Piskunov et al. 1997; Wood et al. 1996), and allows us to fix the absolute wavelength scale to better than 10 km s$^{-1}$.

The strongest Fe XVIII source is $\beta$ Ceti; a single Gaussian fit is shown in Figure 2. The red line depicts the Gaussian stellar emission convolved with the FUSE instrumental line profile (Wood et al. 2001), and demonstrates that the line is fully resolved. The FUSE instrument provides redundant spectral coverage, such that two detector channels (SiC 2A and 1B) observe the Fe XVIII spectral region. This redundancy allows us to confirm the detection of weak lines, as well as quantify systematic errors by analyzing both spectra independently. The Fe XVIII line in $\beta$ Ceti was the only source strong enough to be analyzed by a Gaussian fit. Despite the low signal-to-noise of the other detections, we were still able to measure the centroids of emission. Results are summarized in Table 2.

Table 2. Fe XVIII 975 Å Fit Parameters

| HD # | other name | FUSE Detector | Cen. Vel.[1] C III (km/s) | Cen. Vel.[1] Fe XVIII (km/s) | FWHM Fe XVIII (km/s) | $f$ (Fe XVIII) ($10^{-14}$ ergs cm$^{-2}$ s$^{-1}$) | $\lambda_{\rm CIII}-\lambda_{\rm FeXVIII}$ (Å) |
|---|---|---|---|---|---|---|---|
| 4128 | $\beta$ Cet | SiC 2A | 13 ± 9 | 2 ± 9 | 77 ± 9 | 3.6 ± 0.2 | 2.19 ± 0.03 |
| | | SiC 1B | 15 ± 9 | –4 ± 9 | 86 ± 9 | 3.4 ± 0.3 | 2.22 ± 0.03 |
| 34029[2] | $\alpha$ Aur | | | | | | |
| 197481 | AU Mic | SiC 2A | | | ~ 45 | ~ 3.5 | 2.21 ± 0.03 |
| | | SiC 1B | | | | | |
| 20630 | $\kappa$ Cet | SiC 2A | | | ~ 75 | ~ 1.2 | 2.22 ± 0.03 |
| | | SiC 1B | | | ~ 85 | ~ 1.8 | 2.23 ± 0.03 |

[1]The line velocity relative to the star responsible for the emission.

[2]Capella is a close binary, and therefore we are unable to determine the Fe XVIII line properties for the individual stars (Young et al. 2001).

## 4. Conclusions

The coronal forbidden line Fe XVIII (975Å) has been observed with FUSE in several targets (Figure 1). This line is excellent for studying the dynamics of coronal plasma because it is not contaminated by blends with other lines, unlike Fe XXI (1354Å). Interstellar absorption in the neighboring C III (977Å) line can be used to calibrate the absolute wavelength scale to better than 10 km s$^{-1}$.

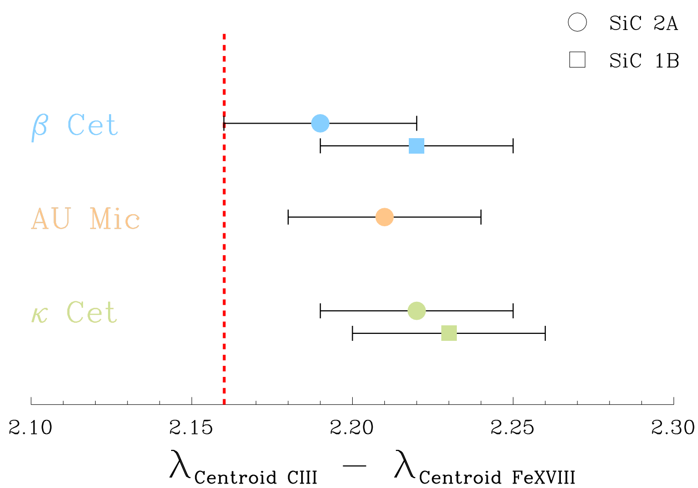


Figure 3. The centroid differences and their errors between the C III line and the Fe XVIII line for three stars. The rest wavelength difference is indicated by the thick dashed red line. All targets show a difference greater than that implied by the rest wavelengths.

The strongest Fe XVIII source is $\beta$ Ceti. A single Gaussian successfully characterizes the Fe XVIII stellar emission (Figure 2). The line is fully resolved at the spectral resolution of FUSE, and therefore, the instrumental broadening is negligible. The rotational broadening is also small, $v \sin i \sim 3.0$ km s$^{-1}$ (Gray 1982). The line width is *not* larger than the expected thermal broadening in $10^7$ K coronal plasma, therefore the nonthermal broadening is very small.

For the two targets with ISM absorption, the central velocities of the Fe XVIII are consistent with 0 km s$^{-1}$, while the C III lines are significantly redshifted relative to the radial velocity of the stellar photosphere. Figure 3 depicts the centroid difference between the C III line and the Fe XVIII line. The rest wavelength difference is the thick dashed red line. All targets show a difference greater than that implied by the rest wavelengths. Transition region lines, such as C III, typically are redshifted, suggesting plasma downflows. The Fe XVIII line is not redshifted significantly and indicates that the coronal plasma is confined, presumably by closed magnetic field structures.

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