The EUV Spectrum of \( \kappa \) Ceti in a Quiescent Phase

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Abstract:

The spectrum of \( \kappa \) Cet in the region 80–370 Å observed by EUVE Spectrometers is discussed to investigate the transition region and the corona of the star. The medium wavelength spectrum of the star appears to be very similar to a moderately active Sun and no evidence exists of flare-like lines observed in many active stars by EUVE. Several emission lines of moderately ionized iron (from Fe\textsuperscript{IX} to Fe\textsuperscript{XVII}) are identified and used together with IUE observations to evaluate the differential emission measure (DEM). The DEM peaks at about \( 3 \times 10^6 \)K, a value typical of solar active regions. Comparison of observed and synthetic spectra are performed using Arcetri code, including both Arcetri and CHIANTI databases.

1. Introduction

The star \( \kappa \) Ceti (HD 20630, G5 V) is slightly smaller than the Sun \( (R_* / R_\odot = 0.93) \) and lies 9.3 pc from the Earth.

It is a solar like star that is well known for its chromospheric and coronal activity, detection of strong emission in Ca\textsuperscript{II} by Wilson & Bappu in 1957, by the bright H and K emission of Mg (Rego & Fernández-Figueroa 1979) and by the strong flare activity reported by Robinson & Bopp, (1987) for the He\textsuperscript{I} 5876 Å line.

Clear evidence of a transition region and a corona surrounding the star is given by the detection of He\textsuperscript{I} line 10830 Å, by Zirin (1976) and by several transition regions lines that have been measured by IUE (Rego et al. 1980) and Fernández-Figueroa et al. (1981)

The star has also been observed with the Einstein Observatory and EXOSAT, Schmitt et al. (1987). Einstein, EXOSAT and IUE observations have been used to model a multi-temperature differential emission measure distribution and to infer constraints on the energy balance in the outer atmosphere of the star (Monsignori Fossi et al. 1986).

Models of transition regions of solar like stars, similar to \( \kappa \) Cet, have been extensively studied by Jordan (1969,1992), Landini et al. (1985), and Jordan et al. (1986, 1991) with the aim to have some insight in the problem of heating their high temperature outer atmospheres.

All the information concerning the coronal model has been supplied by instruments with very poor spectral resolution (Pallavicini et al. 1988). The

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EUV E Spectrometers offers the unique possibility to detect single line emission
and investigate the differential emission measure with high temperature detail.

2. Observation and Data Reduction

Kappa Ceti was observed with the EUVE spectrometers as part of a Guest
Observing program submitted by Brunella Monsignori Fossi, so early deceased,
and Carole Jordan.

The observation lasted from October 12, 1994, 02h53m UT to October 14,
19h41m UT, and covered the short (70–190 Å, SW), medium (140–380
Å, MW) and long (280–760 Å, LW) extreme ultraviolet range with a spectral
resolution of $\Delta \lambda \approx 0.5, 1,$ and 2 Å, respectively.

The final exposure times in seconds were 127966 s for the SW section,
130328 s (for MW), and 125482 s (for LW).

Line fluxes were obtained fitting gaussian line profiles with fixed FWHM
(different in each channel) and a linear continuum; the S/N ratio was calculated
over 7 pixels (the resolution of the three channels) and used to evaluate the
uncertainty on the measured fluxes.

The resulting wavelength calibrated spectra for SW, MW and LW channels,
corrected with the detector effective areas, are reported in the middle panels of
Figures 1, 2, and 3.

Since we are interested in deriving a model for the DEM over the transition
region as well as the corona of $\kappa$ Cet, we have complemented the EUVE identified
line with other lines observed by IUE. Observations from Oranje (1986) have
been adopted. The IUE lines belong to transitions of ions whose maximum
temperature abundance ranges from $10^{4.7}$ to $10^{3.6}$ K.

Since both the EUVE and IUE lines are present during quiescent phases
of the atmosphere of $\kappa$ Cet their observed fluxes should be directly comparable
and can be used to derive a DEM model for the transition region and the corona
of the star.

3. The $\kappa$ Ceti EUV Spectrum

The observed spectrum of $\kappa$ Cet resulting from the data reduction shows strong
detection (with a S/N ratio greater than 3) only for a few spectral lines especially
for the SW detector. The LW channel shows a very confused spectrum for wavelengths greater than 550 Å. However no strong lines are detected longward
of 370 Å.

It is evident that the spectrum is formed in a rather quiet corona, since
the typical features of a flare spectrum (i.e., Fe XXIV 192.04 Å, Fe XXI 128.7
Å, and Fe XXIII 135.8 Å, Monsignori Fossi et al. 1995) are absent, while the
most prominent lines (i.e., Fe XV 284.15 Å, Fe XVI 335.41 Å, Fe XVI 360.81 Å)
are normally seen in the spectra of moderately active Sun and are indicative of
plasmas at a few million degrees.

The two lines 256.32 Å and 303.78 Å are emitted by the lower and cooler
transition region and belong to the spectrum of Fe II whose maximum abundance
occurs at 5 $10^4$ K.
Figure 1. The SW synthetic spectrum (top panel), the observed spectrum (middle panel), and the S/N ratio (bottom panel) versus wavelength.

In order to constrain the temperature dependence of the DEM, a few lines with S/N ratio ≤ 3 have been included, in addition to all the lines having S/N ratio ≥ 3.

4. The Synthetic Spectrum and the DEM Analysis

The intensity of a spectral line \((i \rightarrow j)\) for an optically thin coronal plasma is given by:

\[
I_{ij} = K \, \text{Ab}(Z) \, e^{-\sigma(\lambda)NH} \int_{T} G_{ij}(T, N_e) f(T) dT \quad \text{ph cm}^{-2} \text{ s}^{-1} \text{ str}^{-1}
\]

where

- \(K\) is a constant which takes into account the properties of the instruments and the star’s distance;
- \(\text{Ab}(Z)\) is the abundance of element \(Z\) relative to \(H\);
Figure 2. The synthetic spectrum for the MW section (top panel) is compared with the observations (middle panel). The S/N ratio is shown in the bottom panel.
Figure 3. The LW synthetic spectrum (top panel), the LW observed spectrum (middle panel), and the S/N ratio (bottom panel) plotted versus wavelength. Since wavelengths greater than 550 Å are mainly second order we have omitted that portion of the spectrum. Features in the synthetic spectrum are labeled with contributing lines. Features detected with S/N ratio better than 2 are marked with “#” in the observed spectrum.
• $f(T) = N_e^2 (dV/dT)$ is the DEM;
• $N_H = \int n_H dh$ is the hydrogen column density between the star and the Earth;
• $\sigma(\lambda)$ is the absorption cross section of the interstellar medium;
• $G_{ij}(T, N_e)$ is a function of the line atomic data and depends on the electron temperature ($T$), and on the electron density ($N_e$).

The column density $N_H$ in the direction of $\kappa$ Cet is assumed to be $2 \times 10^{18}$ cm$^{-2}$ using a mean hydrogen density of $0.07$ cm$^{-3}$ (Paresce 1984); a He I/He II ratio of 0.1 and He II/He I ratio of 0.01 have been assumed. In order to take into account the interstellar absorption, the ISM photoionization cross sections of Rumph et al. (1994) were adopted.

5. The ARCETRI Spectral Code

To evaluate the $G_{ij}(T, N_e)$ functions we have made use of a new version of the Arcetri spectral code (Landini & Monsignori Fossi 1990; Monsignori Fossi & Landini 1994) which has been updated using the new extensive database CHIANTI (Dere et al. 1997). This new version of the Arcetri spectral code will soon be released (Landi & Landini 1997) and includes:

• The calculation of the level population and $G_{ij}(T, N_e)$ functions under the assumption of statistical equilibrium for the most important ions of the isoelectronic sequences of Li, Be, B, C, N, O, F, Ne, Na, Mg, and for the iron ions from Fe VII to Fe XIV. The atomic data necessary to perform the calculation are taken from the CHIANTI database.
• The calculation of level population and $G_{ij}(T, N_e)$ functions for the minor elements (Na, P, K, Ti, Cr, Mn, Co, Zn)
• The evaluation of the $G_{ij}(T, N_e)$ functions for lines of isoelectronic sequences of H, He, Al, Ar, Cl, F, K, P, Si not included in the CHIANTI database. The assumption is made that the population of the upper level occurs via collisional excitation from ground level only.
• The evaluation of the ionization balance for Fe ions of Arnaud & Raymond (1992), together with an updating for the other elements made by Landini & Monsignori Fossi (1991)
• Free-free, free-bound and two-photon emission continuum.

6. DEM Analysis and $N_e$ Diagnostics

Information on the DEM model $f(T)$ may be derived by combining the measured fluxes of a set of spectral lines with the knowledge of the appropriate contribution functions $G_{ij}$. The numerical procedure we have used to evaluate the DEM
function $f(T)$ is an application of the “maximum entropy method”, described by Monsignori Fossi & Landini (1991a,b).

The resulting DEM is shown in Figure 4. For each line used in the DEM procedure a point is plotted in Figure 4 at the temperature where the line is formed and at the DEM value necessary to fit the observations. It is worth noting that most of the lines are fitted by the DEM within the error bars.

Unfortunately it is not possible to use the intensity ratio technique to determine the mean electron density $N_e$ of the emitting plasma since no pair of density sensitive lines of the same ion is available in the observed spectrum. Nevertheless we are confident that the electron density should not be greater than $3 \times 10^9 \text{ cm}^{-3}$ since for higher values other spectral lines (Fe xiii 203.8 Å lines) should have been detected, and Fe xiii 192 Å line should have been much weaker than observed. The adopted electron density is therefore $10^9 \text{ cm}^{-3}$.

7. Synthetic Spectra and Further Line Identification

Using the DEM model shown in Figure 4 and the new version of the Arcetri Spectral Code (Landi & Landini 1997) we have computed the synthetic spectrum of $\kappa$ Cet for the wavelength range covering all the three channels of the EUVE spectrometer. The results are shown in the top of Figure 1 for the SW section, of Figure 2 for the MW section, and Figure 3 for the LW section.
Through a comparison between the calculated synthetic spectrum and the observed one we are able to make some further identification of some weak lines. Only lines whose S/N ratio is greater than 2 have been considered.

- In the SW range no feature exceeds a S/N ratio of 2. However the two lines Fe\textsuperscript{XVII} 103.937 Å and Fe\textsuperscript{X} 180.408 Å are predicted by the synthetic simulation; they could be present in the observed spectrum with a S/N ratio slightly larger than 1. Hotter lines (e.g., Fe\textsuperscript{XXI} 128.736 Å) often seen in stars during strong flare activity show extremely low S/N ratios and their absence confirms that κ Cet was in a quiescent phase during the time of the observation.

- The Fe\textsuperscript{X} line at 180 Å can be identified also in the MW range. Other weak MW lines are Fe\textsuperscript{XIV} 211.320 Å, Fe\textsuperscript{XVI} 251.074 Å + Fe\textsuperscript{XIII} 251.955 Å + Fe\textsuperscript{XIV} 252.910 Å and Fe\textsuperscript{XIII} 203.80 Å + 203.83 Å. The theoretical flux for the latter line is a bit too large and probably we could have matched its experimental value better by lowering the assumed electron density of the emitting plasma. Nevertheless the constraint imposed by the Fe\textsuperscript{XII} line at 192 Å did not allow us to lower $N_e$.

- For the LW section a number of features exceeds the S/N ratio equal 2 and are marked by a “#” in the observed spectrum (Figure 3, middle panel). All but one have a counterpart in weak features of the synthetic spectrum that are labeled with the contributing wavelengths. As expected some of them are second order contribution, but O\textsuperscript{III} 374.2 Å, 507.8 Å + 508.2 Å, and 525.8 Å, and Si\textsuperscript{VII} 499.4 Å and 520.7 Å are probably detected at S/N = 2, and Ar\textsuperscript{XVI} 390.9 Å, Ne\textsuperscript{IV} 469.8 Å, and Ne\textsuperscript{VII} 465.2 Å only slightly disagree in wavelength.

8. κ Ceti and the Quiet Sun

Kappa Cet is a solar-like star and its spectrum is expected to be similar to that of the Sun, though the much weaker signal coming from this star limits the comparison of the spectral features only to the most prominent lines. Differences between the two observed spectra may be due to important characteristics of the κ Cet emitting plasma, and may impose some constraint on the abundances of some elements relative to those of the Sun. For this reason a comparison between the EUV spectra of these two stars may be interesting.

In order to make such a comparison a spectrum measured with the Coronal Diagnostic Spectrometer (CDS) from the Solar Heliospheric Observatory (SOHO) has been used. The spectrum represents the total counts integrated over a slit covering a $4 \times 240$ arcsec$^2$ and includes an active region on the Sun, under conditions similar to those expected in κ Cet during the time of the EUVE observation.

The instrument and its characteristics are described in Harrison et al. (1995).

The CDS spectrometers have 6 spectral windows that cover a spectral range from 151 to 785 Å, similar to that of EUVE SW, MW, and LW channels. Nevertheless, since the EUVE LW channel is strongly affected by interstellar
Figure 5. The MW spectrum of $\kappa$ Cet (bottom panel) is compared with CDS-SOHO spectrum of a solar active region (top panel). The HeII 303.8 Å line has been suppressed in the solar spectrum.

absorption, and the SW spectral range is only marginally observed by CDS, we restrict our comparison only to the CDS Normal Incidence (NIS) channel 308–381 Å and to the Grazing Incidence (GIS) channels 151–221 Å and 256–338 Å. A composite solar spectrum is produced and comparison with MW EUVE section is shown in Figure 5.

The comparison has illustrates the following features:

- The two spectra are very similar, especially for the strongest lines of the spectrum.

- There could be some differences in the abundances of Si and Mg relative to Fe since some relatively strong solar lines (Mg IX 368 Å) are not visible in the EUVE spectrum.

- A longer exposure time of $\kappa$ Cet could have helped in identifying several weaker lines observed in the solar spectrum which could have made it possible to evaluate the electron density of the emitting source, and to verify the abundances of the elements.
9. Conclusions

- The EUV spectra of the solar-like star $\kappa$ Cet observed with the SW, MW, and LW spectrometers of the EUVE satellite have been used to evaluate a model for the DEM of the source. Since the observation occurred during a quiet phase, and we are interested in developing a DEM model of the transition region as well as of the corona, we have complemented the EUVE measured fluxes with an observation carried out with the IUE spectrometer in the range 1200–1800 Å.

- Two lines of Fe\textsc{xi}i and Fe\textsc{xiii} have been used to put constraints on the electron density of the corona of the star.

- The derived DEM has been used to calculate the synthetic spectrum and identify a few weak lines. In particular the LW section shows the presence of several O, Ne and Si lines that, although at a very low S/N ratio, should deserve a more detailed study to investigate the chemical composition of the transition region and corona of this star.

- The spectrum of $\kappa$ Cet is very similar to that measured by the CDS on SOHO looking at a solar active region.

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